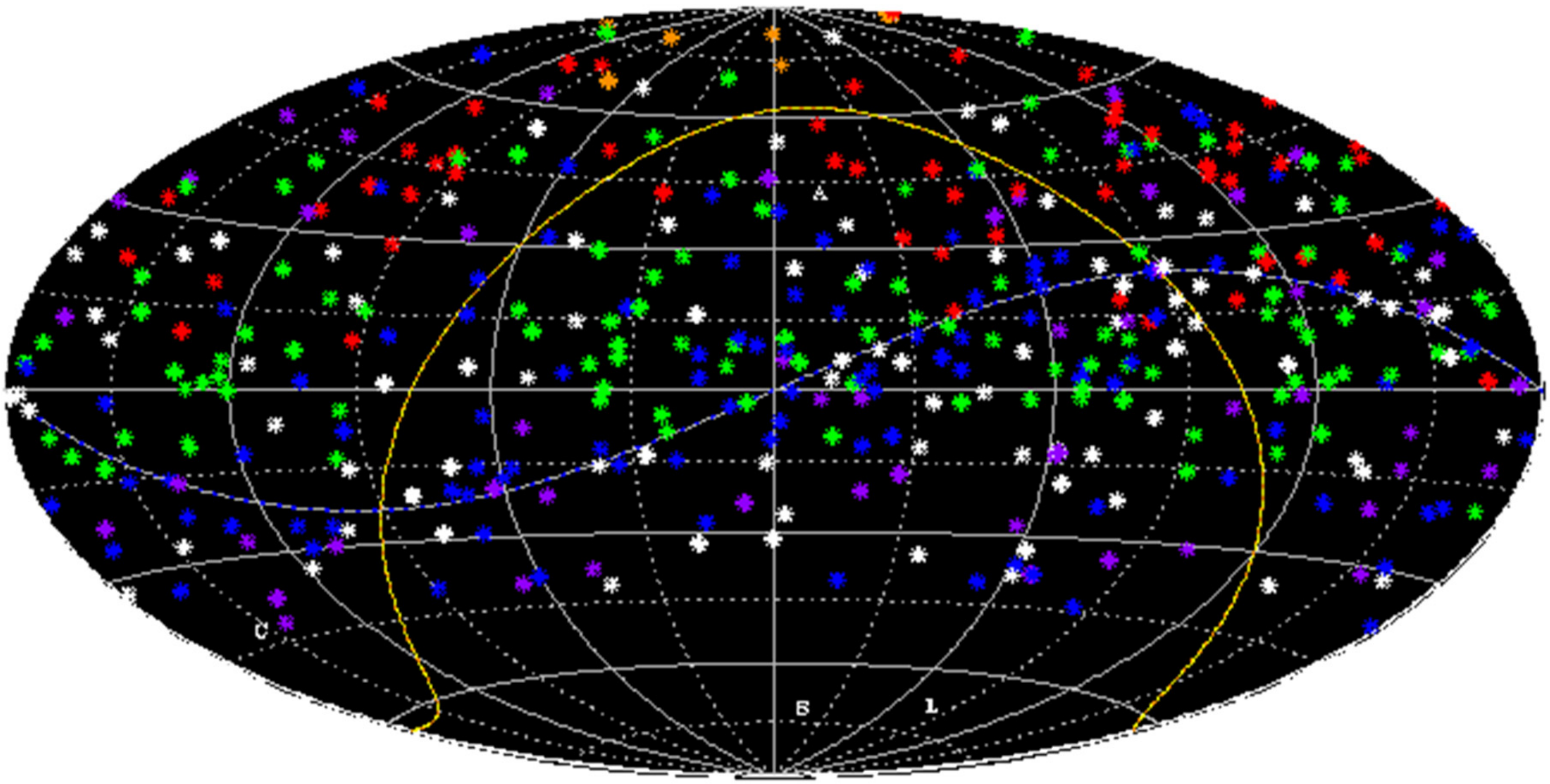
# Celestial Reference Frames

## A proposal for ESA-DSN Collaboration




Christopher S. Jacobs

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*25 March 2011*

# Overvie w

- Historical Perspective on Astrometry & Navigation
- Principles of VLBI radio interferometry
- Status of current radio-based celestial frames
  - ICRF2: wavelength 3.6cm, 3.4K objects, 40-100 μas
  - K-band: wavelength 1.2cm, 0.3K objects, 100-250 μas
  - X/Ka: wavelength 9mm, 0.5K objects, 200-300 μas

- ESA-DSN radio collaboration: complementary geometry
  - Benefits southern cap, Declination accuracy

- Gaia/optical to VLBI/radio: 5-10 μas frame tie

  70-100 μas potential as independent accuracy verification

# Collaborators

- ICRF2 Working Group (S/X-band, 3.6cm)

  C. Ma chair

  E.F. Arias, G. Bianco, D.A. Boboltz, S.L. Bolotin, P. Charlot, G. Engelhardt, A.L. Fey, R.A. Gaume, A.-M. Gontier, R. Heinkelmann, C.S. Jacobs, S. Kurdubov, S.B. Lambert, Z.M. Malkin, A. Nothnagel, L. Petrov, E. Skurikhina, J.R. Sokolova, J. Souchay, O.J. Sovers, V. Tesmer, O.A. Titov, G. Wang, V.E. Zharov, C. Barache, S. Bockmann, A. Collioud, J.M. Gipson, D. Gordon, S.O. Lytvyn , D.S. MacMillan, R. Ojha

- KQ Collaboration (1.2cm,7mm or 24, 43 GHz)

  G.E. Lanyi, P.I.

  D.A. Boboltz, P. Charlot, A.L. Fey, E. B. Fomalont, B.J. Geldzahler, D. Gordon, C.S. Jacobs, C. Ma, C.J. Naudet, J.D. Romney, O.J. Sovers, L.D. Zhang

- X/Ka-band Collaboration (9mm, 32 GHz)

  C.S. Jacobs, P.I.

  J. Clark, C. Garcia-Miro, S. Horiuchi, V.E. Moll, L.J. Skjerve, O.J. Sovers

# Navigation & Astrometry:
# Historical Perspective

*Figure credit:* www.arsmachina.com/images/compass7012-1.jpg

# Paradigm of “Sailing by the stars”

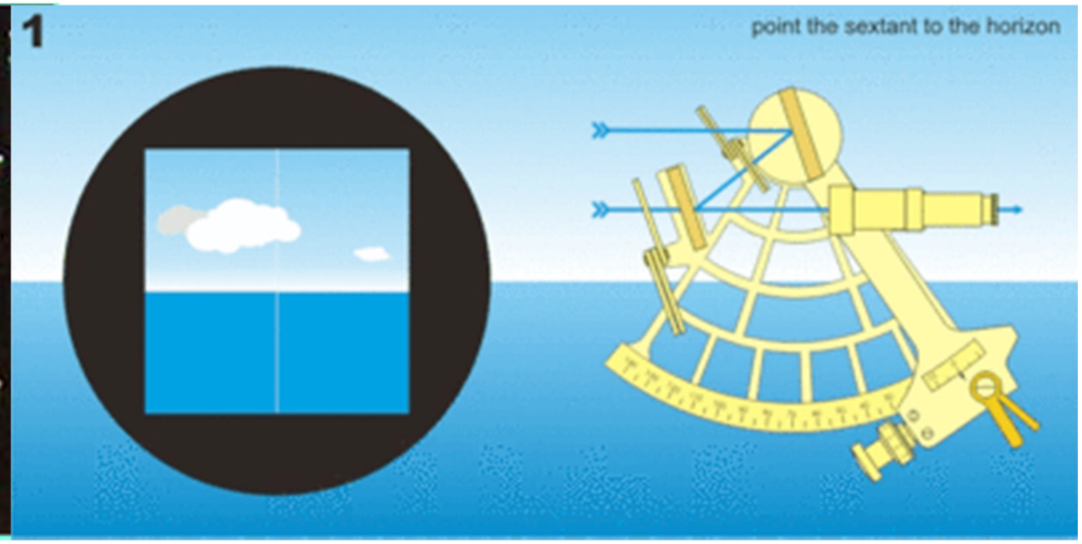



Photo Credit: Dimitry Bobroff, www.ludmillaalexander.com

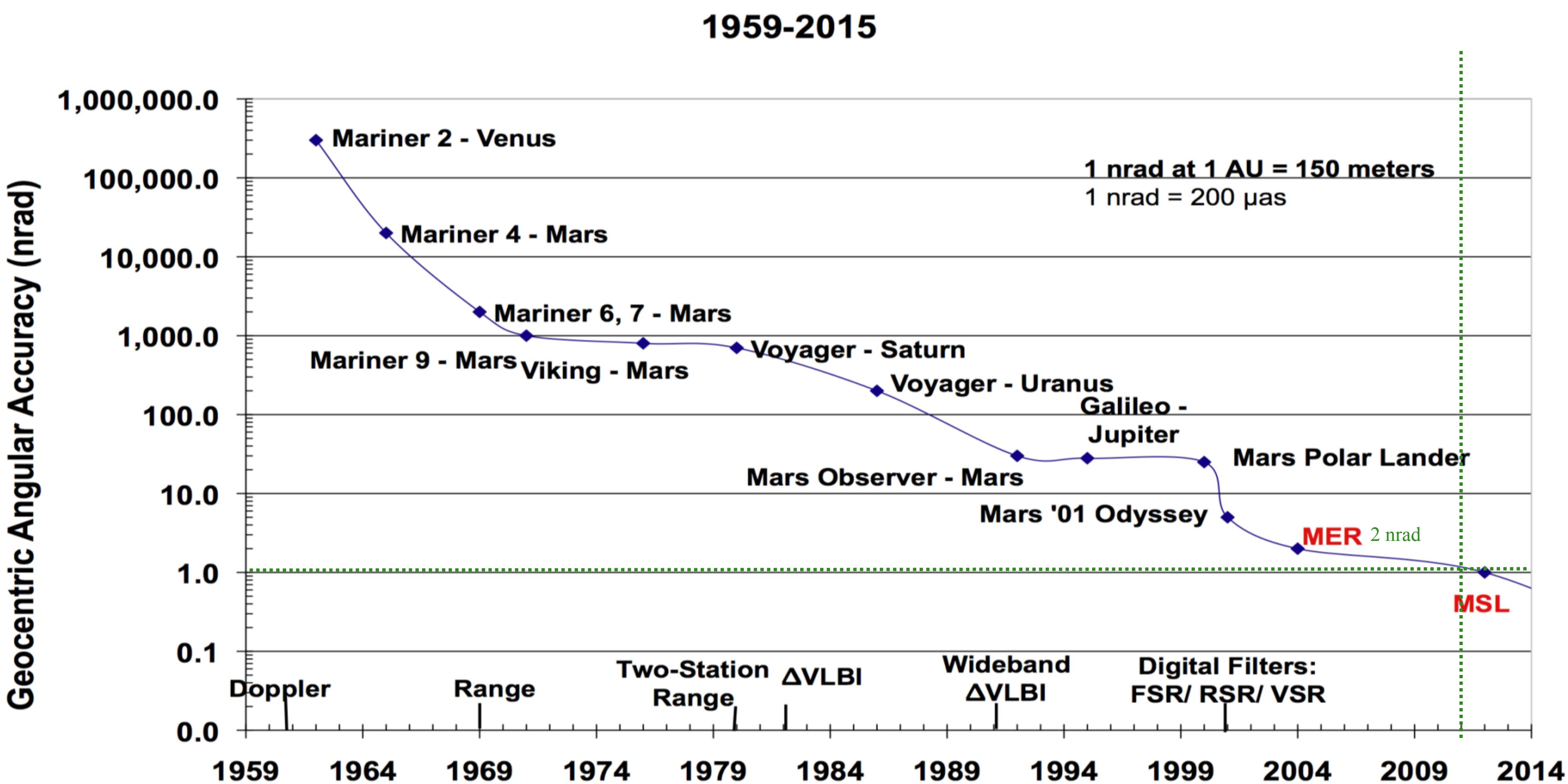


Credit for sextent/octant: en.wikipedia.org/wiki/Sextant (GNU Free Doc license)

# History of Astrometry: Star positions

| | | | |
|---|---|---|---|
| 130 B.C. | Hipparchus | Precession | 50 asec/yr |
| *Telescope era:* | | | |
| 1718 A.D. | Halley | proper motions | 1 asec/yr |
| 1729 | Bradley | annual aberration | 20 asec |
| 1730 | Bradley | 18.6yr nutation | 9 asec |
| 1838 | Bessell | parallax | ~ asec |
| 1930s | Jansky, Reber | Radio astronomy | |
| 1960s | *several groups* | Very Long Baseline Interferometry (VLBI) invented | |
| 1970s | " | VLBI | sub-asec |
| 1980s | " | " | few 0.001 asec |
| 1990s | " | " | < 0.001 asec |
| 2000s | " | " | ~0.0001 asec |
| 2010s | Gaia | Optical astrometry | 25-70 μas for V=16-18 quasar |
| 2010s | ESA-DSN? | X/Ka 9mm VLBI | 70 μas 0.3 Jansky quasar |

# DSN Navigation System Accuracy




Credit: J.E. Patterson.

# How Does VLBI Work?

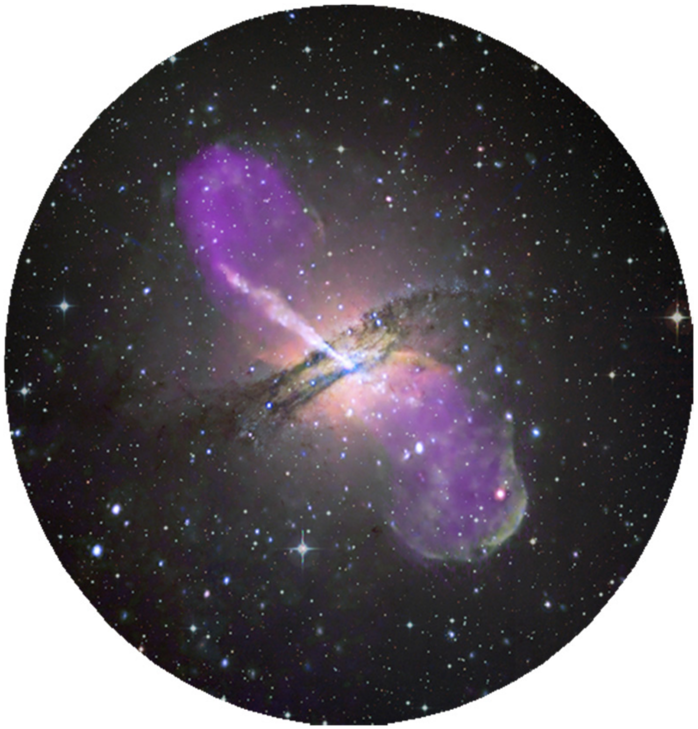
## *The Concept:*

## Point Source at Infinity

Figure credit: math.yorku.ca/infinity_old/NewMembers/NewMembers.html

# Point Source at Infinity as Reference Beacon

**How does VLBI work?**



Credit: *chandra.harvard.edu/photo/2008/cena/cena_multi.jpg*

- **Point source at infinity as a direction reference**

  **Extragalactic "nebulae" idea from**

  **Laplace (1749-1827) and**

  **Wm. Herschel (1738-1822): *in 1785***

  ***realized that "nebulae" likely very distant***

  \`On the Construction of the Heavens,' Ph.Trans.Roy.Soc., 1785, p. 213 ff.

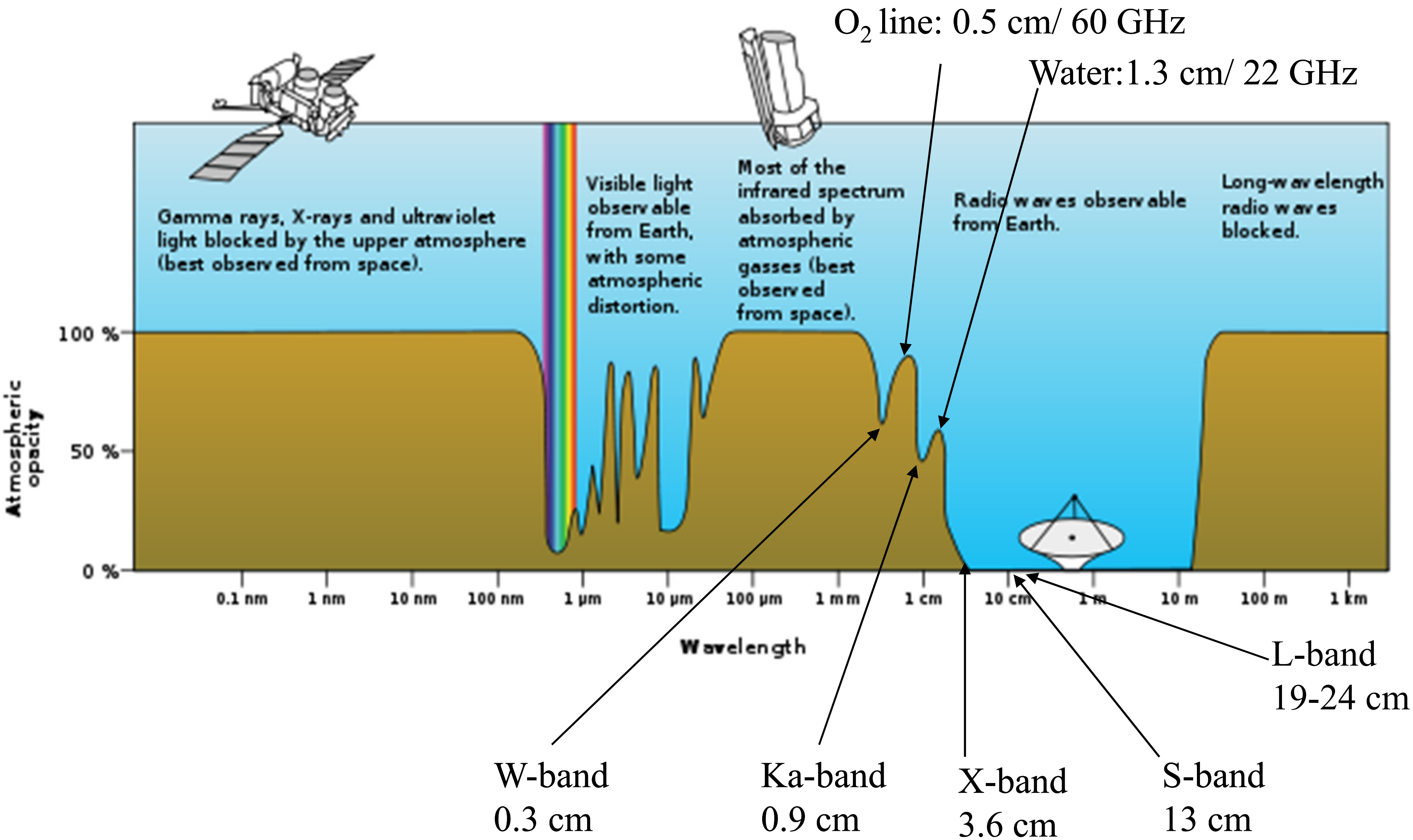
- **Advantage: sources don't move**

**BUT at a distance of a *billion* light years . . .**

- **The price to be paid is**

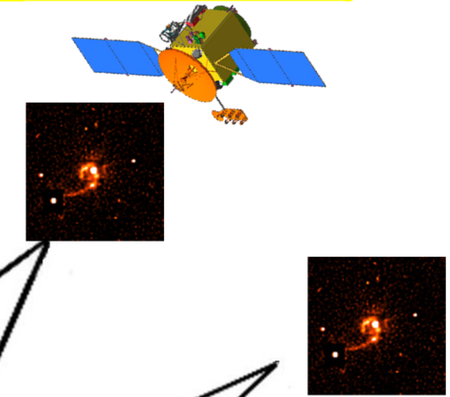
| | |
|---|---|
| **Very weak sources** | **1 Jy = 1.0E-26 watt/m**2/Hz** |
| **need lots of square meters** | **=> 34 - 70m Antenna** |
| **lots of Hz bandwidth** | **=> 0.1 to 4 Gbps** |
| **low system temperature** | **=> Tsys = 20 - 40 Kelvin** |

# Why observe in Radio? The 'Window'




*Credit: NASA; http://en.wikipedia.org/wiki/Radio_window*

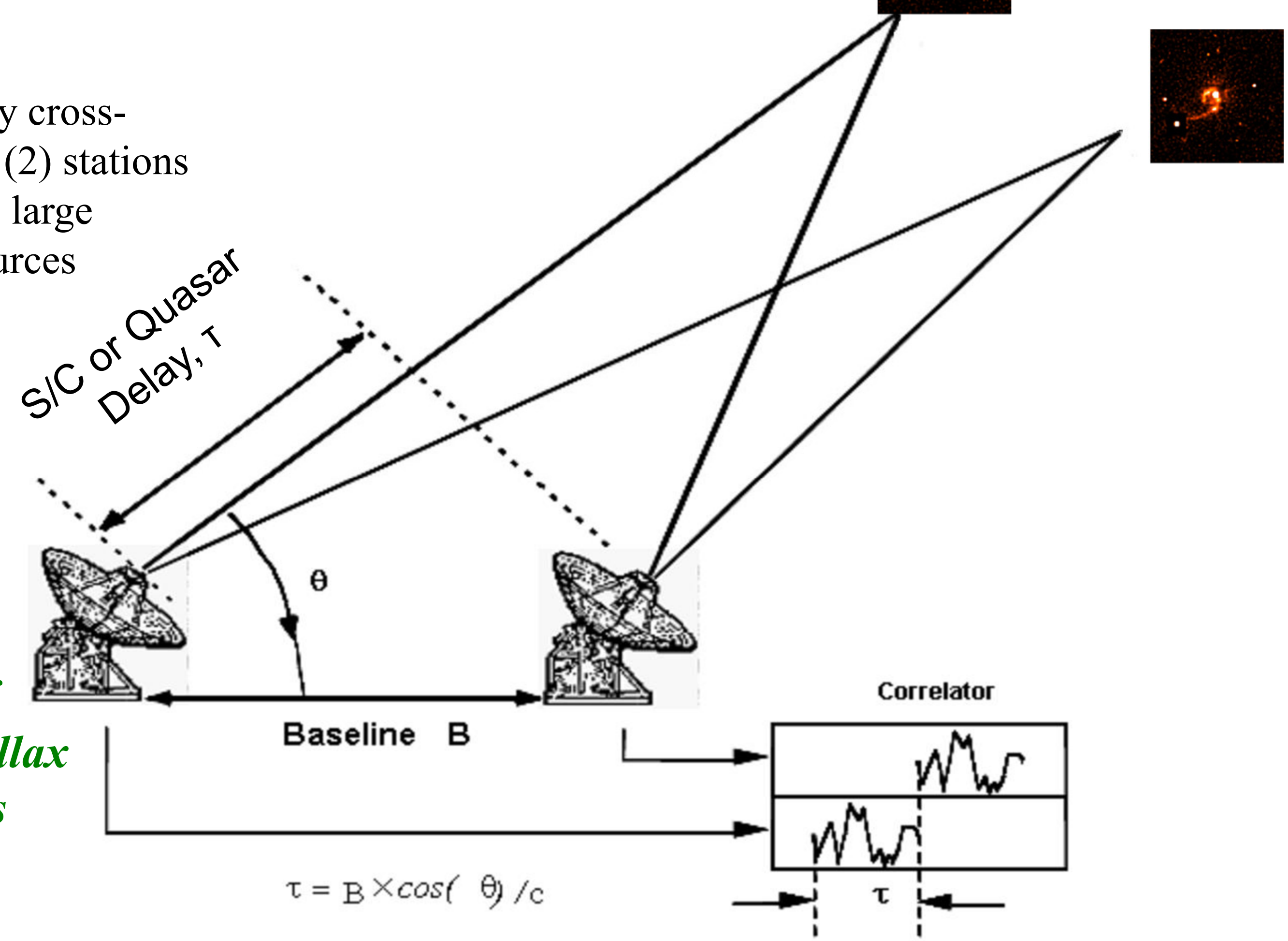
# VLBI is station differenced range
# To determine arcs between quasars



- Measures geometric delay by cross-correlating signal from two (2) stations
- Double-differencing cancels large portion of common error sources

  *-instrumental effects*
  *-baseline uncertainty*
  *-clock errors*
  *-media effects*

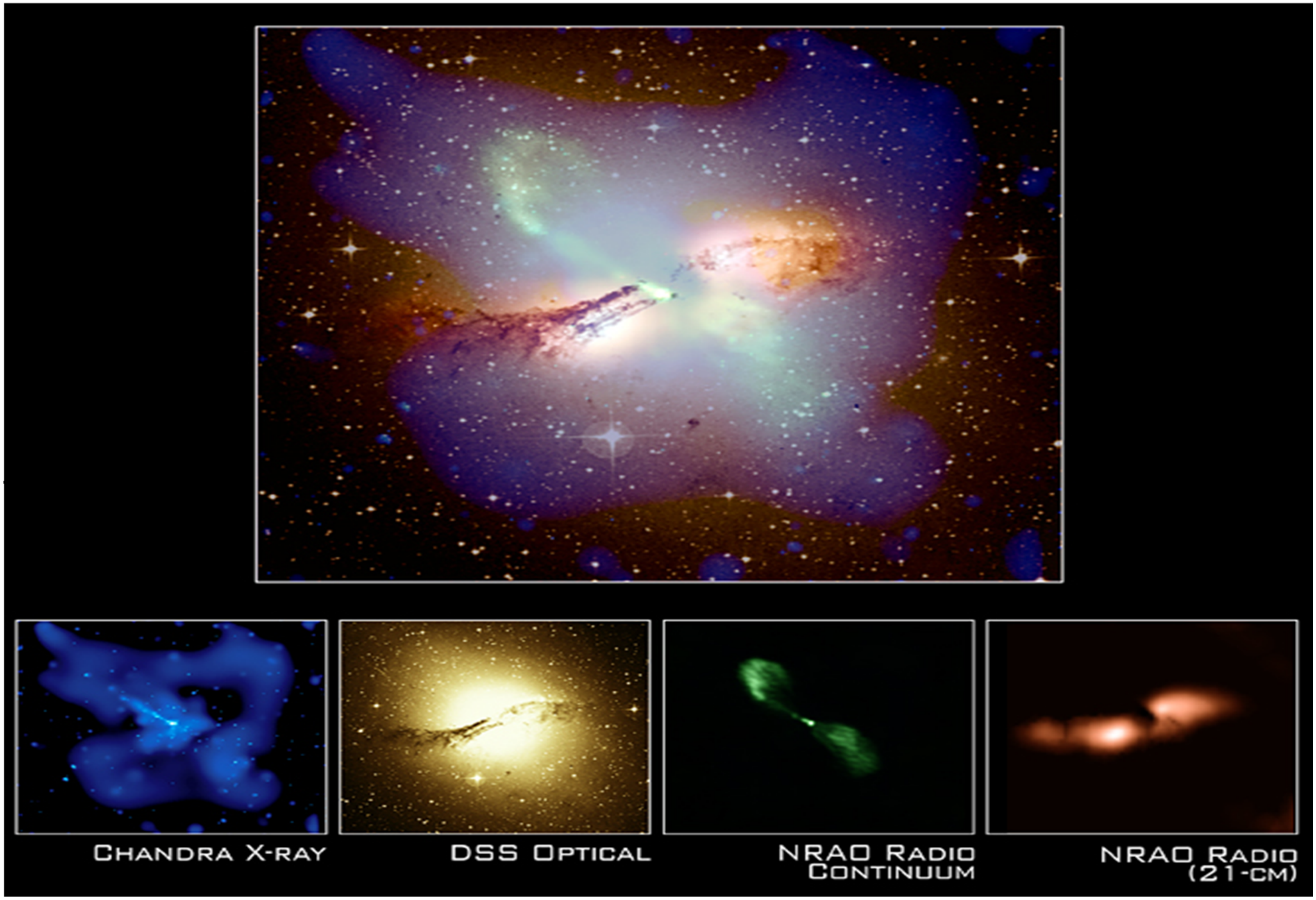
- ***Builds on foundation of zero proper motion/parallax due to distance of quasars***





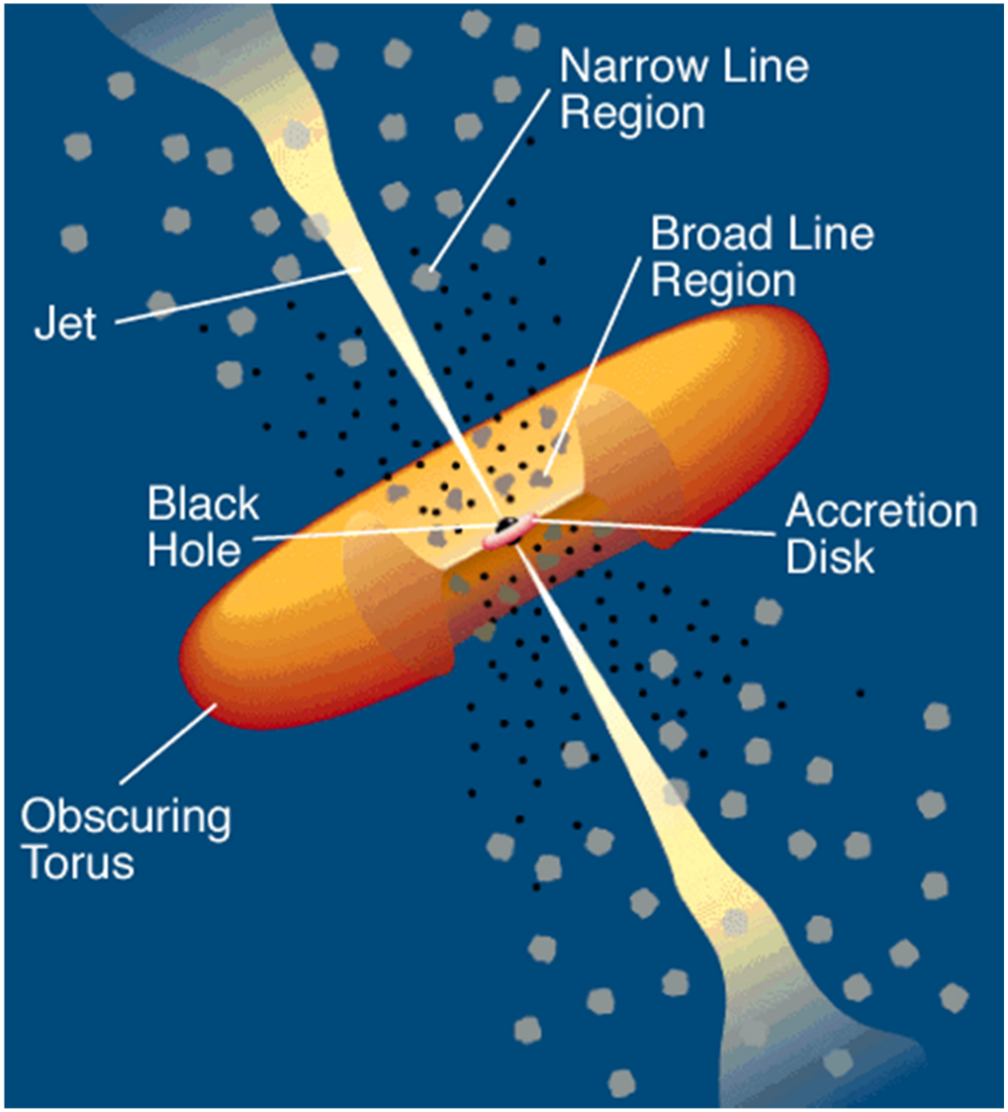

Credit: J.S.Border, C.D Edwards, J.E. Patterson, D. Shin

# AGN Centaurus-A in X-ray, Optical, Radio




Credits: X-ray (NASA/CXC/M. Karovska et al.); Radio 21-cm image (NRAO/VLA/Schiminovich, et al.), Radio continuum image (NRAO/VLA/J.Condon et al.); Optical (Digitized Sky Survey U.K. Schmidt Image/STScI)

# Active Galatic Nuclei (AGN) schematic




http://heasarc.gsfc.nasa.gov/docs/objects/agn/agn_model.html

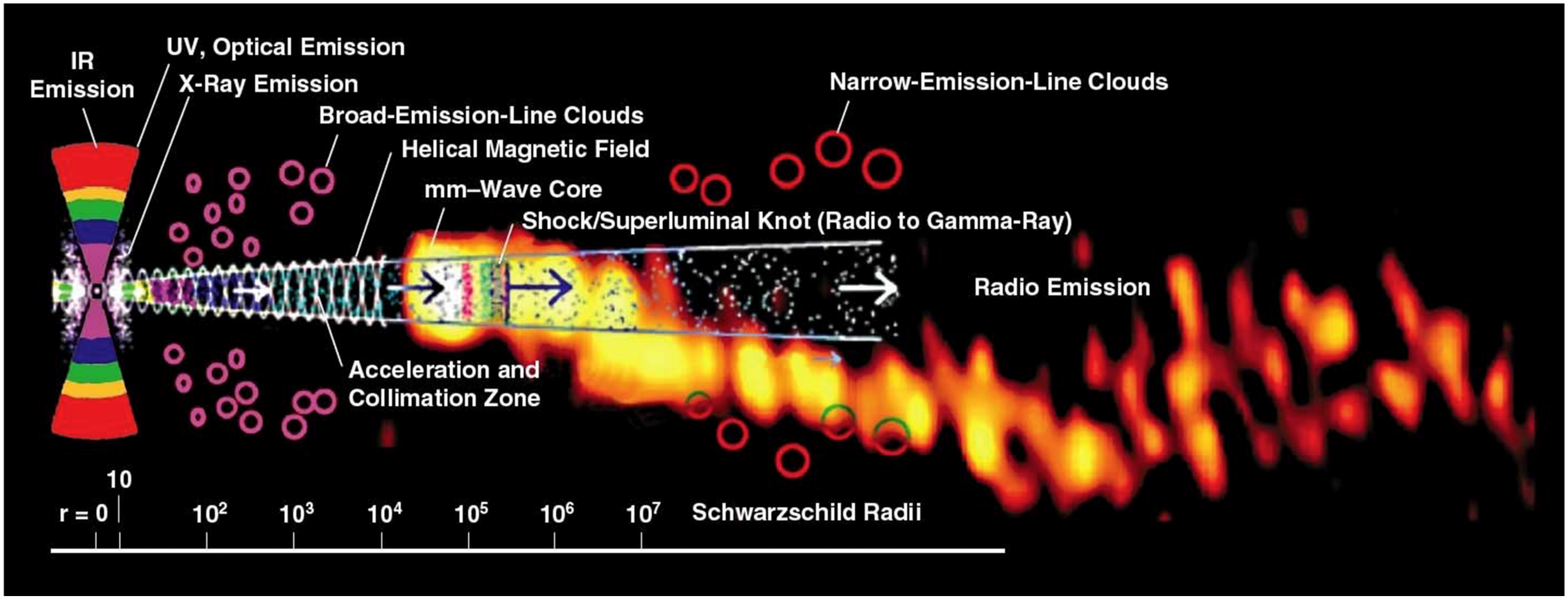
Credit: C.M. Urry and P. Padovani

Schematic of
*Active Galactic Nuclei*
Redshift z~ 0.1 to 5
Distance:
billions light years
*Parallax = 0*
*Proper motion*
< 0.1 nrad/yr

Centroid of radiation
Gets closer to central
engine (black hole)
As one goes to higher
frequencies, therefore,

Ka-band (9mm, 32 GHz)
is better than
X-band (3.6cm, 8.4 GHz)

# Active Galactic Nuclei (*Marscher*)

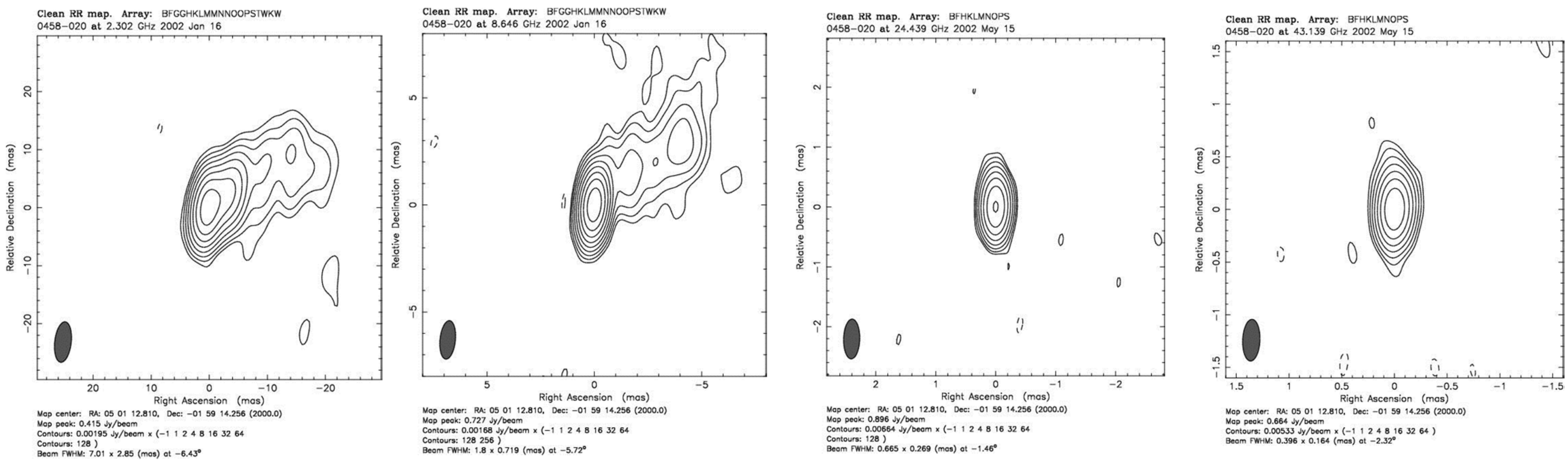



R~0.1-1 μas 1mas

Features of AGN: *Note the Logarithmic length scale.*
"Shock waves are frequency stratified, with highest synchrotron frequencies emitted only close to the shock front where electrons are energized. The part of the jet interior to the mm-wave core is opaque at cm wavelengths. At this point, it is not clear whether substantial emission occurs between the base of the jet and the mm-wave core."

Credit: Alan Marscher, `Relativistic Jets in Active Galactic Nuclei and their relationship to the Central Engine,' Proc. of Science,VI Microquasar Workshop: Microquasars & Beyond, Societa del Casino, Como, Italy, 18-22 Sep 2006. Overlay (not to scale): 3 mm radio image of the blazar 3C454.3 (Krichbaum et al. 1999)

# Source Structure vs. Wavelength




S-band
2.3 GHz
13.6cm

X-band
8.6 GHz
3.6cm

K-band
24 GHz
1.2cm

Q-band
43 GHz
0.7cm

Ka-band
32 GHz
0.9cm

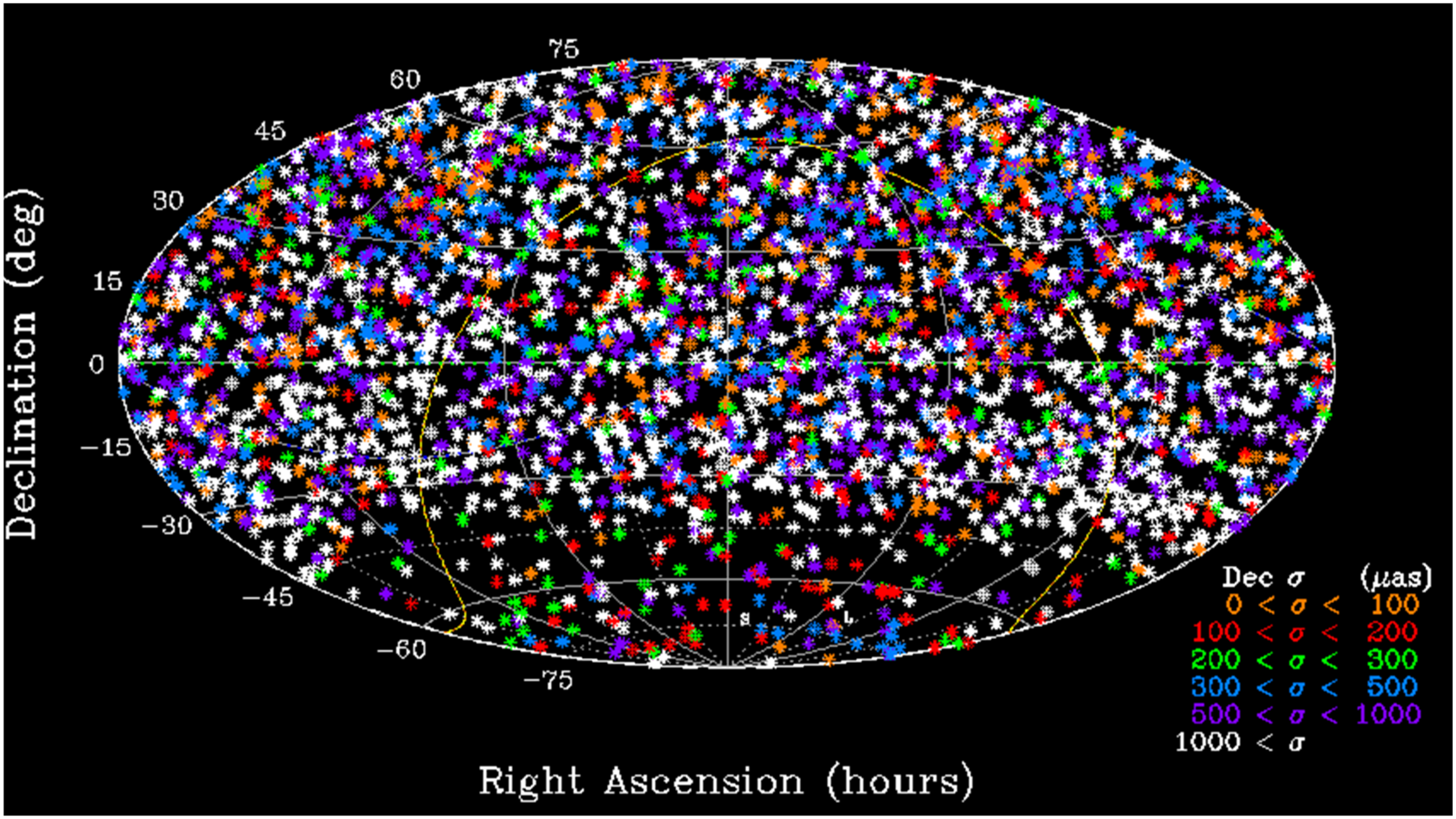
The sources become better ----->

*Image credit: P. Charlot et al, AJ, 139, 5, 2010*

# Current Status of
# Celestial Reference Frames
# at radio wavelengths:

**S/X ICRF2:** 3.6cm, 8 GHz
**K-band:** 1.2cm, 24 GHz
**X/Ka-band:** 9mm, 32 GHz

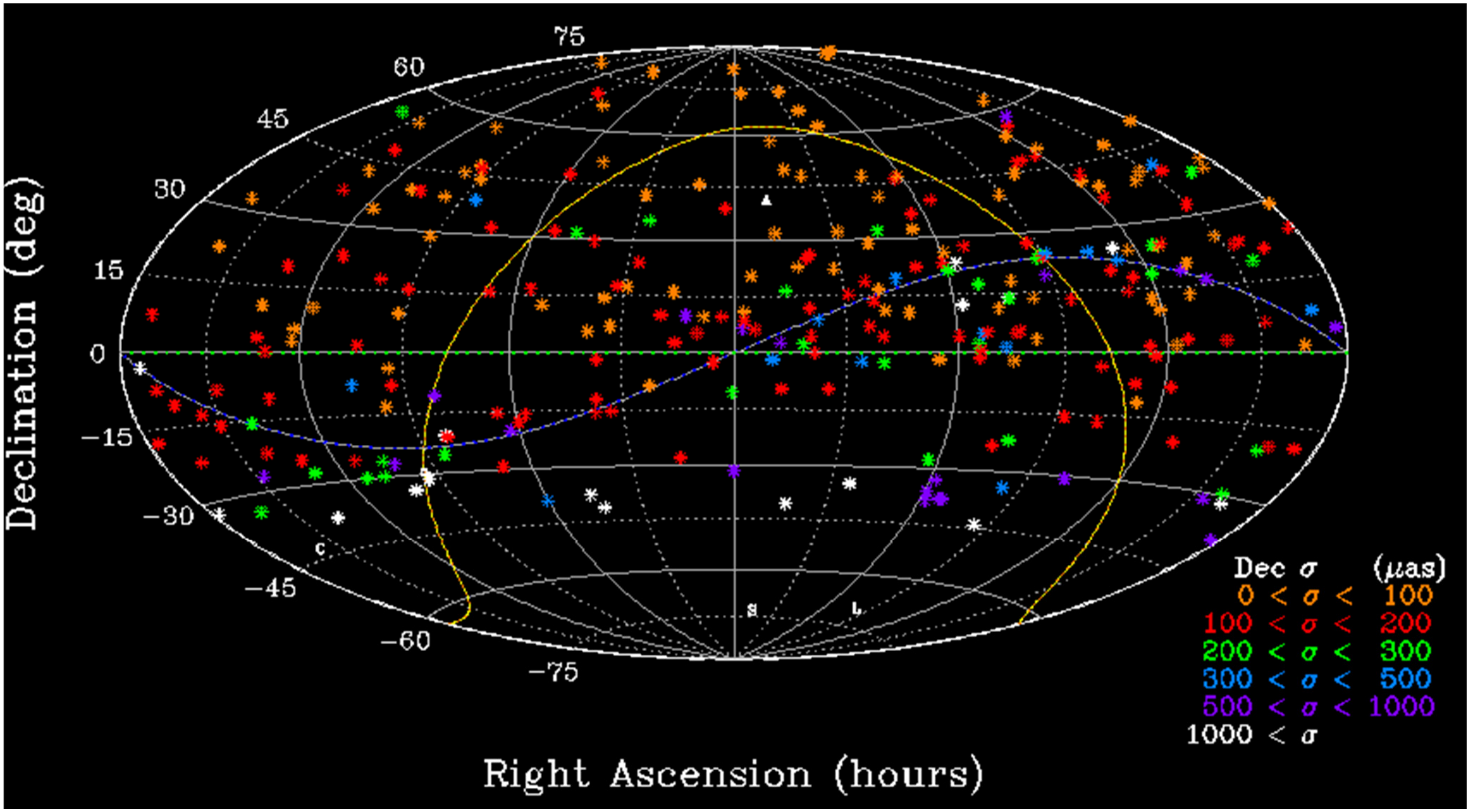
# ICRF2 S/X 3.6cm: 3414 sources




40 μas floor. ~1200 obj. well observed, ~2000 survey session only

Credit: Ma et al, eds. Fey, Gordon, Jacobs, IERS Tech. Note 35, Germany, 2009

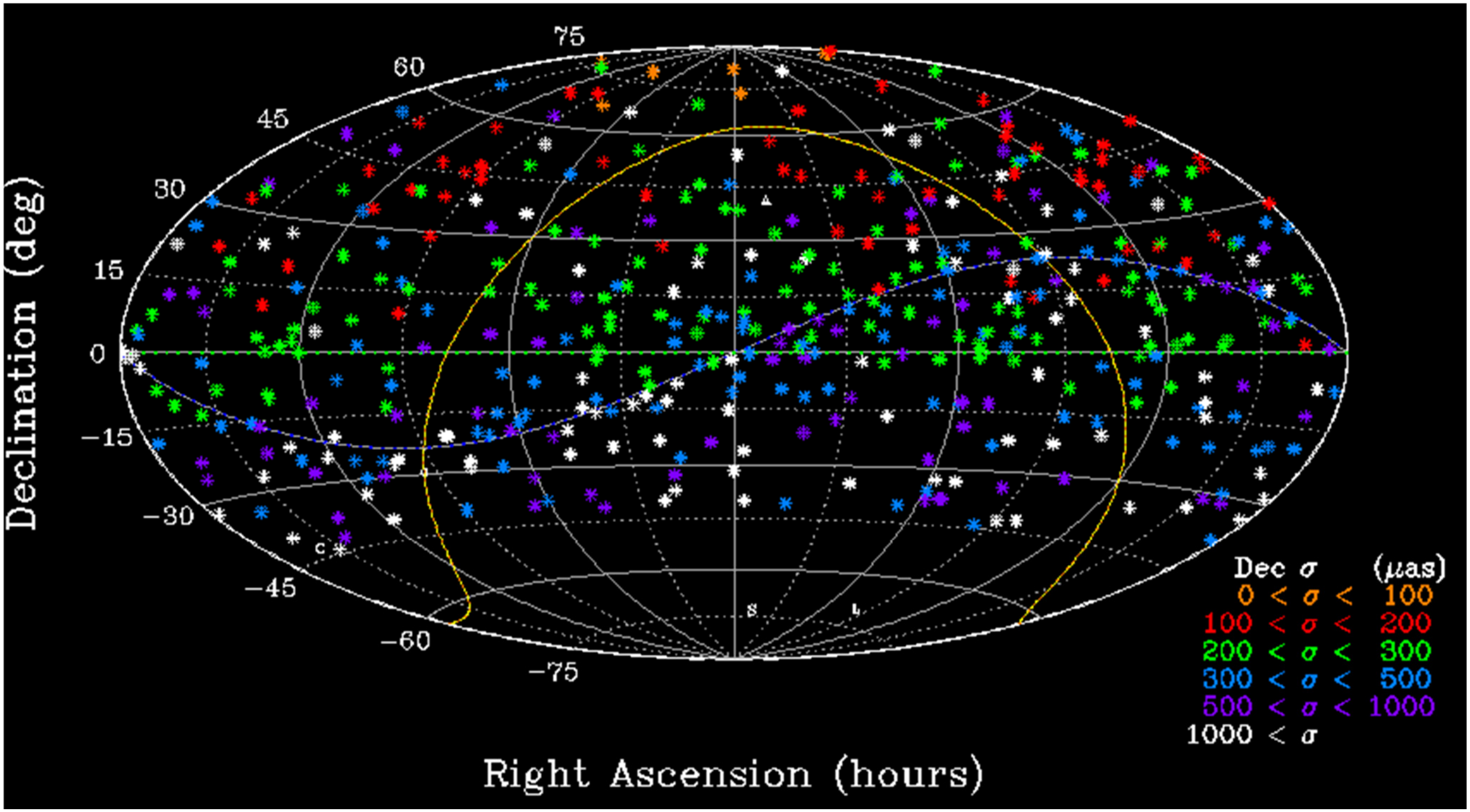
# K-band 1.2cm: 278 Sources




VLBA all northern, poor below Dec. -30˚. ΔDec vs. Dec tilt= 500 μas

Credit: Lanyi et al, AJ, 139, 5, 2010; Charlot et al, AJ, 139, 5, 2010

# X/Ka current results: 455 Sources

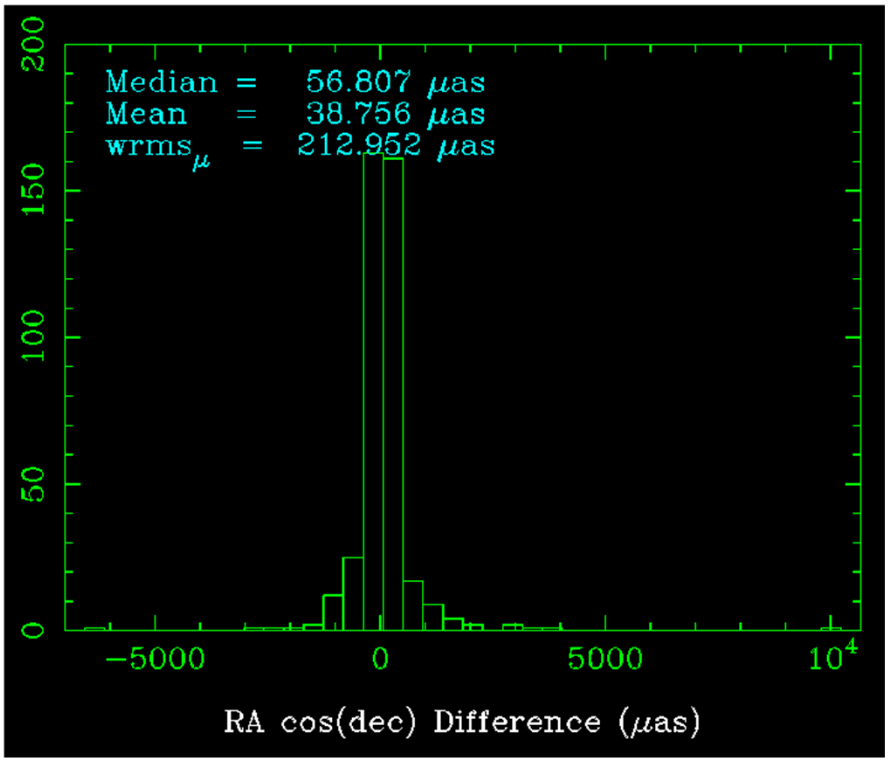


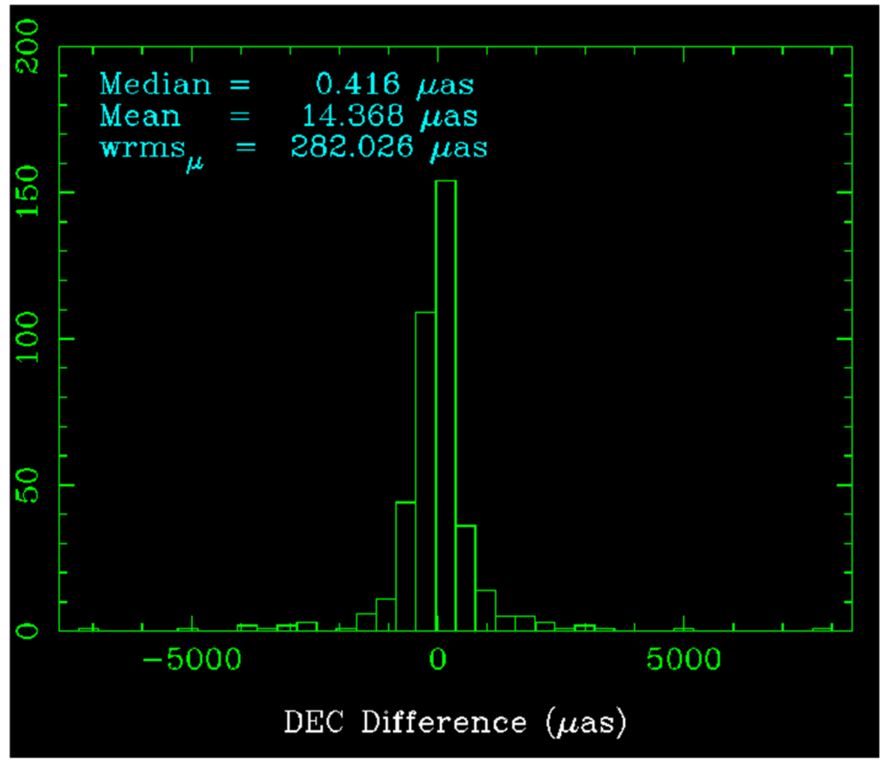

Cal. to Madrid, Cal. to Australia. Weakens southward. No ΔDec tilt

Credit: Jacobs et al, EVGA, Bonn, Germany, 2011

# 9mm (X/Ka) *vs.* ICRF2 at 3.6cm (S/X)

**Accuracy of 404 X/Ka sources vs. S/X ICRF2 (current IAU standard)**




**RA: 213 μas = 1.0 nrad**

**Dec: 282 μas = 1.4 nrad**

*Credit: X/Ka: Jacobs et al, EVGA, Bonn, Germany, 2011*
*S/X ICRF2: Ma et al, editors: Fey, Gordon & Jacobs, 2009*

# Error Budget for VLBI X/Ka Radio Reference Frame

***The Tall Tent Poles***



*Figure credit: S. Myneni ssrl.slac.stanford.edu/research/highlights_archive/organo-cl_compounds.html*

# Improving X/Ka VLBI

## Systems Analysis shows dominant Errors are

- Limited SNR/sensitivity
  - already increasing bit rates: 112 to 448 Mbps. Soon to 896?
- Instrumentation: already building better hardware
  - Ka-band phase calibrators, Digital Back Ends (filters)
- Troposphere: better calibrations being explored for turbulent variations in signal delay

- **Weak geometry in Southern hemisphere**
  - Limits accuracy to about 1 nrad (200 μas) level in Declination
  - No observations below Declination of -45 Deg!
  - DSN has only one southern site: Canberra, Australia (DSS 34)
  - Need 2nd site in the Southern hemisphere

# Attacking the Error budget

- **SNR can be improved +8 dB!**
- Instrumentation:
  Phase calibration with test signals
  Digital Baseband Conversion & Filtering
- Troposphere cals: WVR
- Southern Geometry

# Accuracy has been limited by SNR

**Solution:**

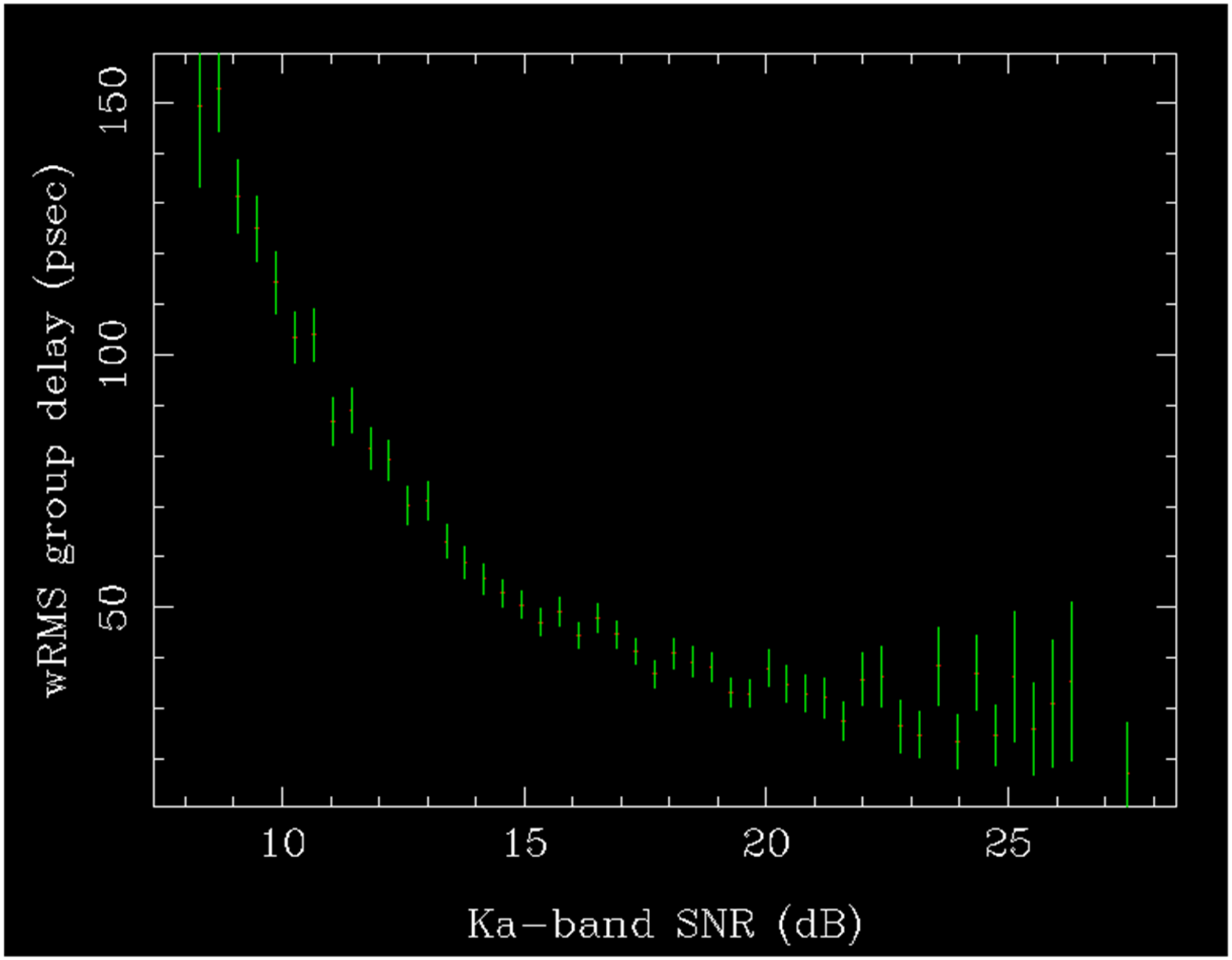
**1) More bits:**
**4X operational**
**8X R&D**
**in ~6 months**
**yields +5 dB SNR**

**16X in 2-3 years**
**32X in 3-5 years**

**2) Ka pointing**

**Now with improved Pointing calibrations ~3 dB more SNR**

**Total vs. early passes +8 dB SNR increase!**

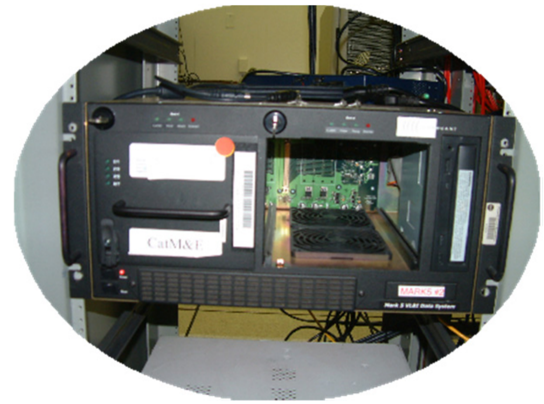



**Data scatter has been SNR limited for SNR < 15 dB**

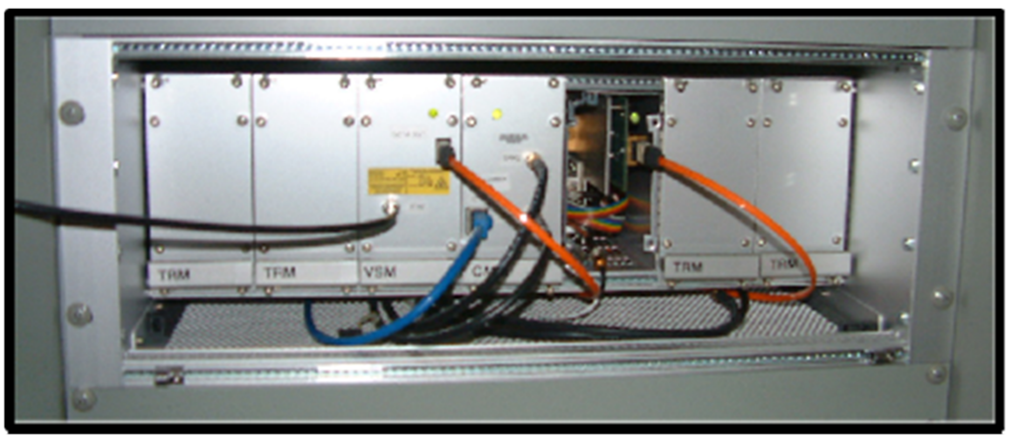
# *Higher data rate hardware being developed*

IF select switch:
12 inputs allows
multiple bands,
multiple antennas

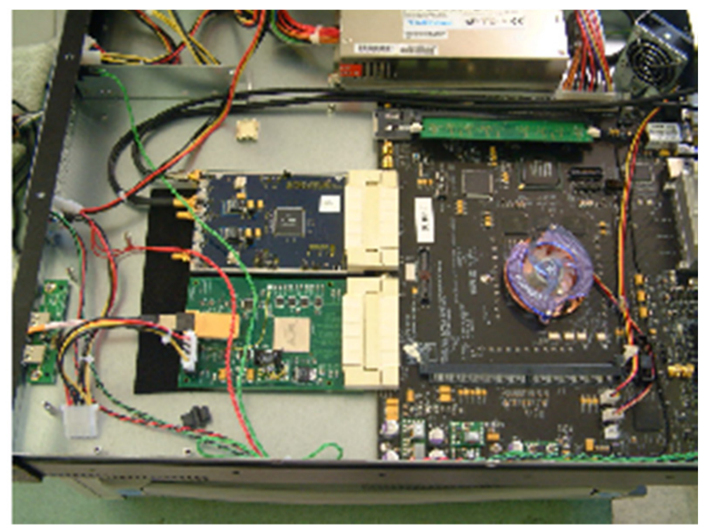
Mark-5C recorder



Command & Control



Sampler: 1280 MHz, 8-bit/sample



Copper to fiber, **Digital filter**, Format

*Design: Navarro et al., IVS, 2010. Photo credit: Les White*

# Attacking the Error budget

- SNR can be improved +8 dB!

- **Instrumentation:**

  Phase calibration with test signals

  Digital Baseband Conversion & Filtering

- Troposphere cals: WVR

- Southern Geometry

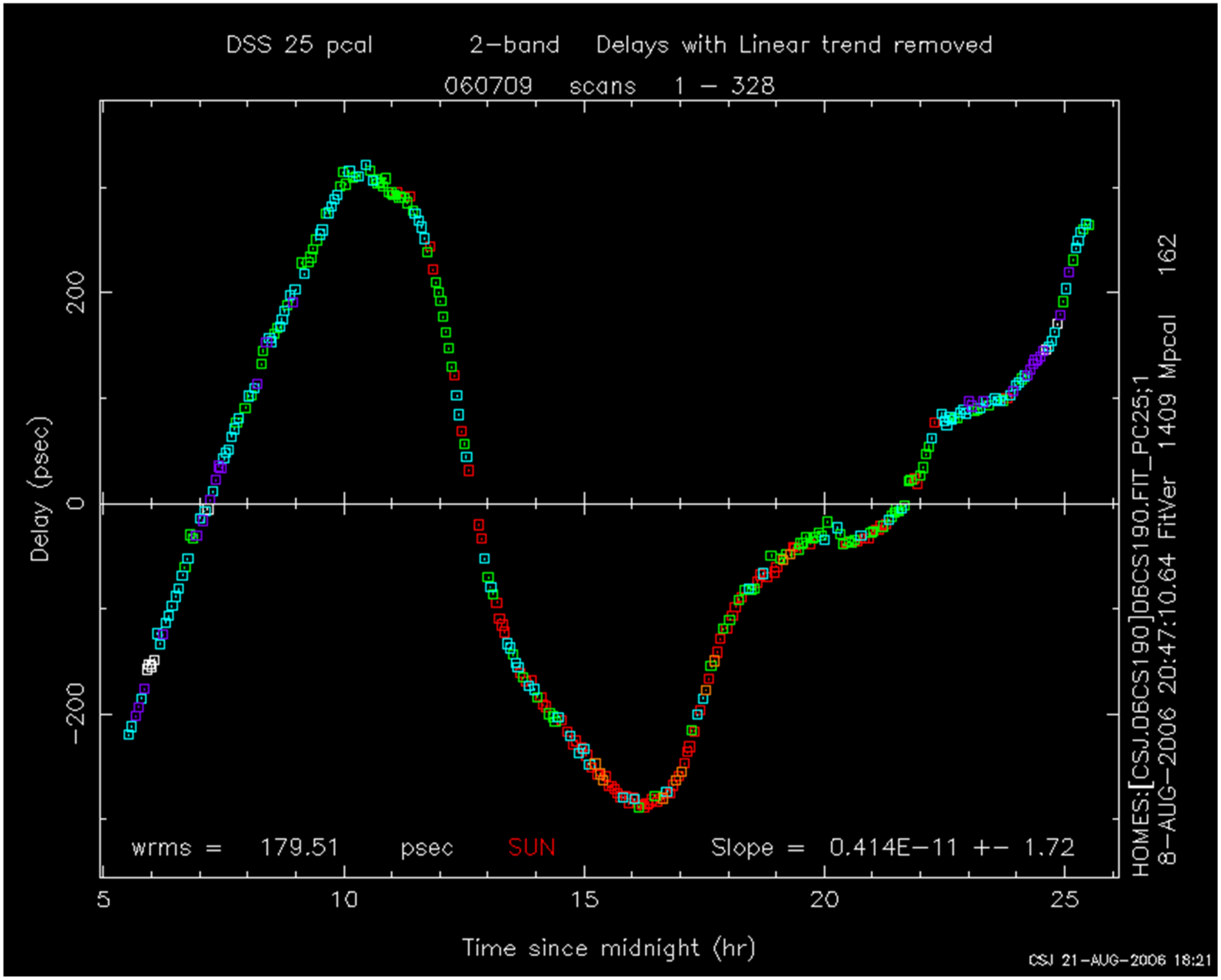
# Need instrumental Phase calibrations

**<u>Problem:</u>**
**180 psec ~diurnal effect**

**<u>Solution:</u>**

**Ka-band Phasecal Prototype Demo'd --- >**

**Units being Built. Operations in ~1 year**




Proto-type shows need for calibrations. *Credit: C. Jacobs, B. Tucker, L. Skjerve*

# Summary of Instrumental Improvements

| Instrument | | MkIV | DBE/Mk5-C | Comment |
|---|---|---|---|---|
| Filters | | Analog 7-pole Butterworth | Digital FIR phase linear | removes phase ripple in channel |
| Spanned bandwidth | | 360 MHz | | Mk4 limit |
| | | | 500 MHz | 1.4X improvement |
| Data rate | @ start | 112 Mbps | | DSN SNR limited |
| | @ max. | 896 Mbps | | trop/inst. limited |
| | @ start | | 2048 Mbps | trop/inst. limited |
| | @ max. | | 4096 Mbps | 6X sensitivity |
| Phase Cal: | HEF/70m | Yes | Yes | |
| | BWG | No | Yes | removes 100s of psec |

# Attacking the Error budget

- **SNR can be improved +8 dB!**
- Instrumentation:

  Phase calibration with test signals

  Digital Baseband Conversion & Filtering

- **Troposphere cals: WVR**
- Southern Geometry

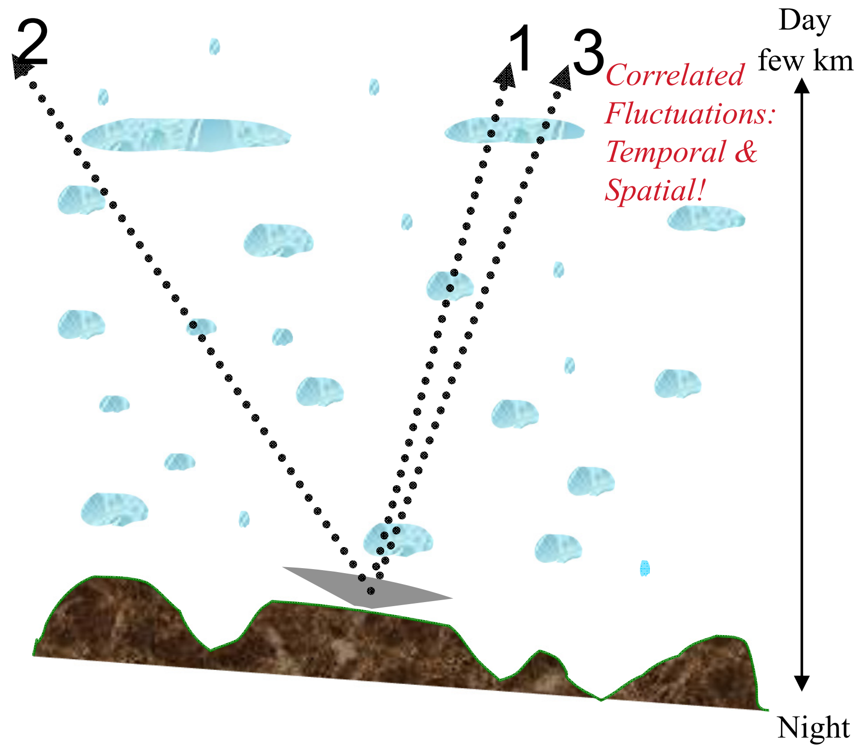
# Troposphere Solution 1: Better Estimation

- Modified Least Squares to account for observation correlations -- both temporal and *spatial*

- Use Kolmogorov frozen flow model of Treuhaft & Lanyi (Radio Sci. 1987)

- Model increases information available to the estimation process
  1) Reduces parameter biases
  2) Reduces parameter sigmas

- Validation: Currently improves agreement X/Ka vs. S/X catalogs by about 10% in Declinations.
  Expect ~30% after SNR & phase cal errors peeled away to reveal troposphere errors.



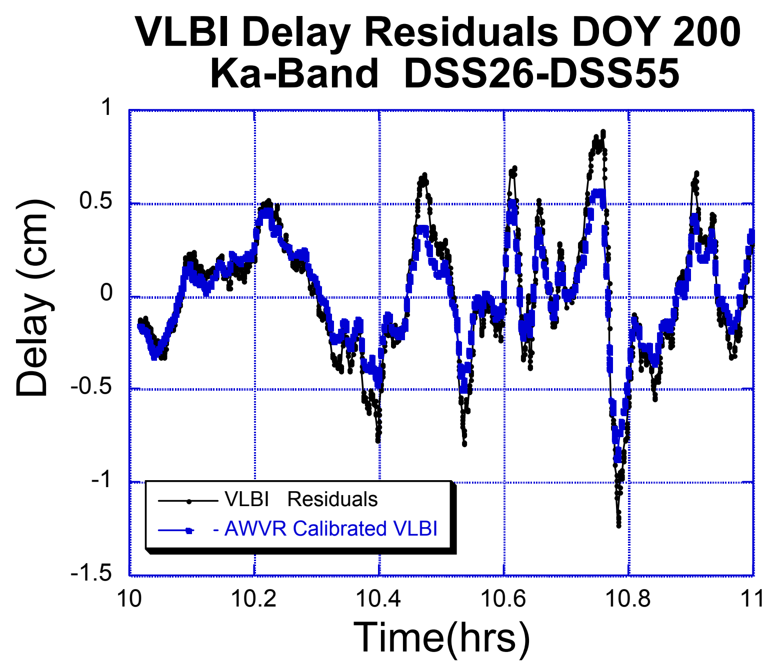
# Calibrating Troposphere Turbulence

- Monitor 22 GHz/1.3cm water (rotational) line brightness temperature along line-of-sight

- JPL Advanced Water Vapor Radiometer
  ~ 1 deg beam better matches VLBI
  improved gain stability
  improved conversion of brightness temperature to path delay

- Demonstrated ~20 μas calibration accuracy Goldstone-Madrid 8000 km baseline using X/Ka phase delays
  *Jacobs et al, AAS Winter 2005.*
  *Bar Sever et al , IEEE, 2007.*

- A-WVRs deployed at Goldstone/Madrid
  Seeking funding for Tidbinbilla, Aus
  not used yet for Operations

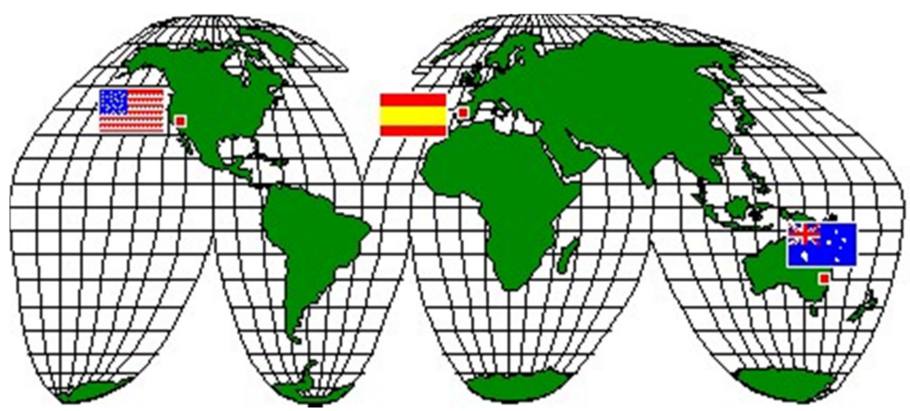


# Attacking the Error budget

- SNR can be improved +8 dB!
- Instrumentation:

  Phase calibration with test signals

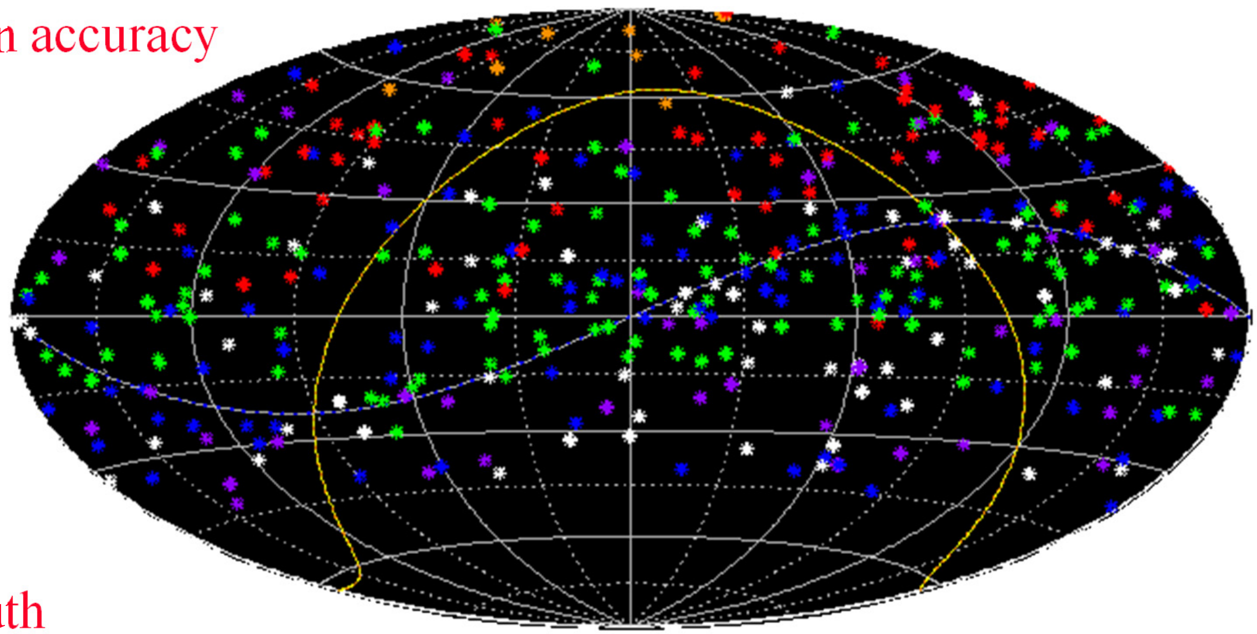
  Digital Baseband Conversion & Filtering
- Troposphere cals: WVR
- **Southern Geometry**



www.spacetoday.org/images/SolSys/DeepSpaceNetwork/NASA_DSN_WorldMap.gif

# Need 2nd Station in South

- No current X/Ka sources have 200 μas Declination accuracy south of equator!



- No coverage of South polar cap (-45 to -90 Dec)

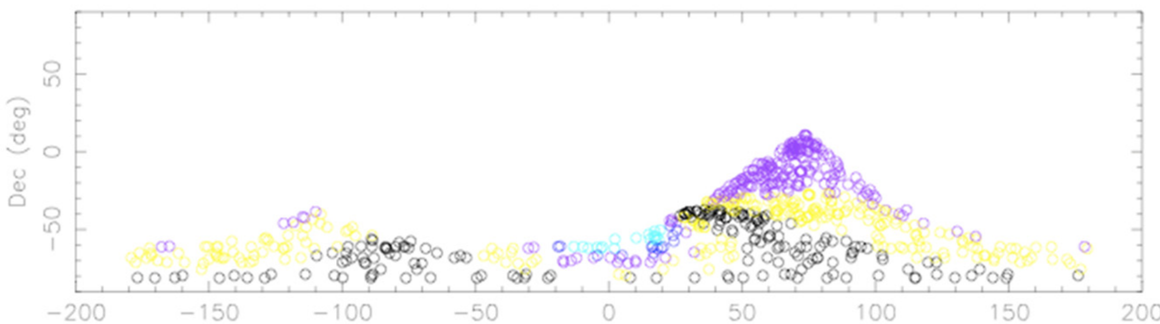
- DSN weakly covers southern Ecliptic: only one strong baseline as California-Spain is weak in south

<u>Declination 1-sigma Precision</u>

| | |
|---|---|
| Orange | 0 - 100 μas |
| Red | 100 - 200 |
| Green | 200 - 300 |
| Blue | 300 - 500 |
| Purple | 500 -1000 |
| White | >1000 |

# Potential Southern VLBI Stations?

- ESA Deep Space Antennas (DSA-1, 2, 3)
  - Cebreros, Spain: duplicate geometry to DSN in Robledo
  - New Norcia/Perth, Australia (helps but only 3000km from DSN Tidbinbilla)
  - **Malargue, Argentina:** Ideal, online mid-2012? NASA/CSIRO collaborate?
    - 35m, X/Ka-band, 9,500 km baseline
    - Dry desert site is good for Ka-band
    - HA-Dec coverage: Tidbinbilla to Malargue:

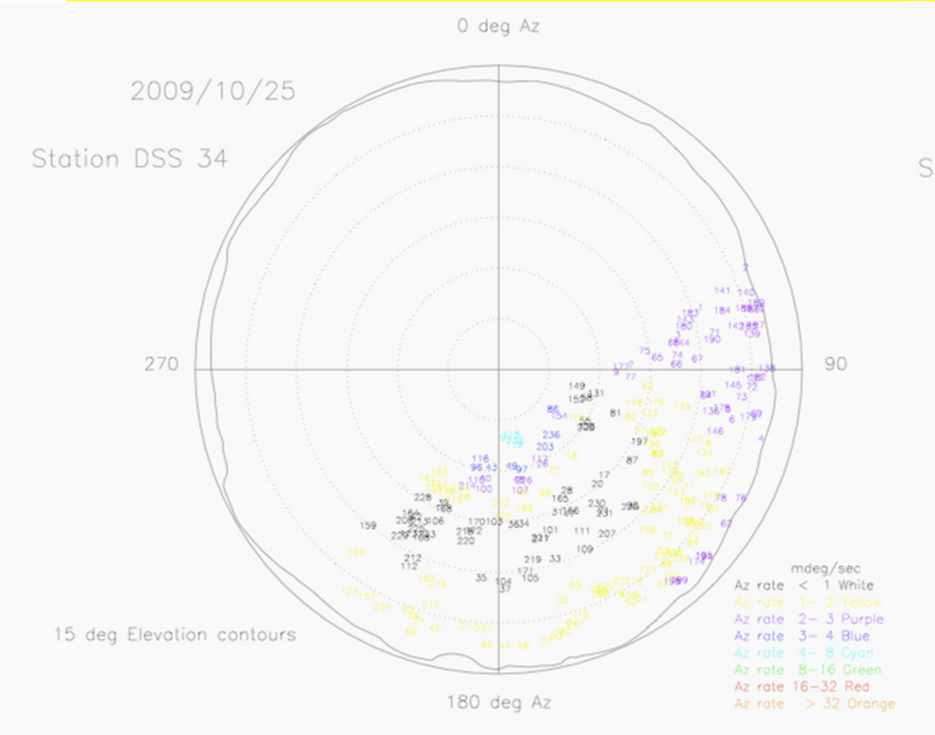


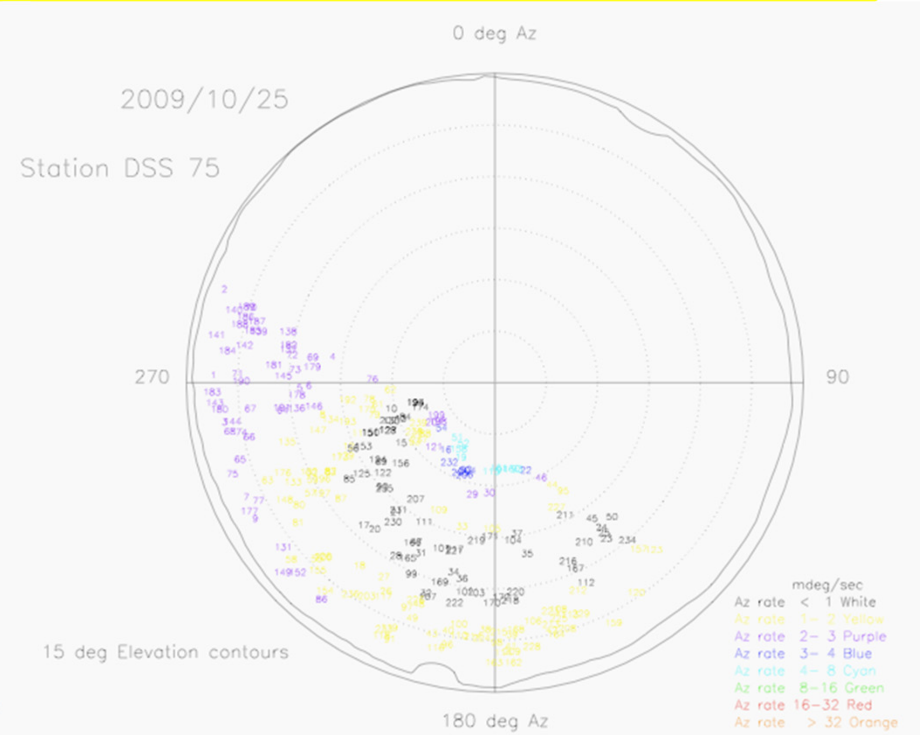

ESA Deep Space Antenna
*35m, Ka-band capable*

- Hart, South Africa
  - Old DSS 51 diameter 26m
    - Was broken ~2yr, Recently repaired
    - Resurfaced in 2005 (0.5mm RMS) efficient to 22 GHz

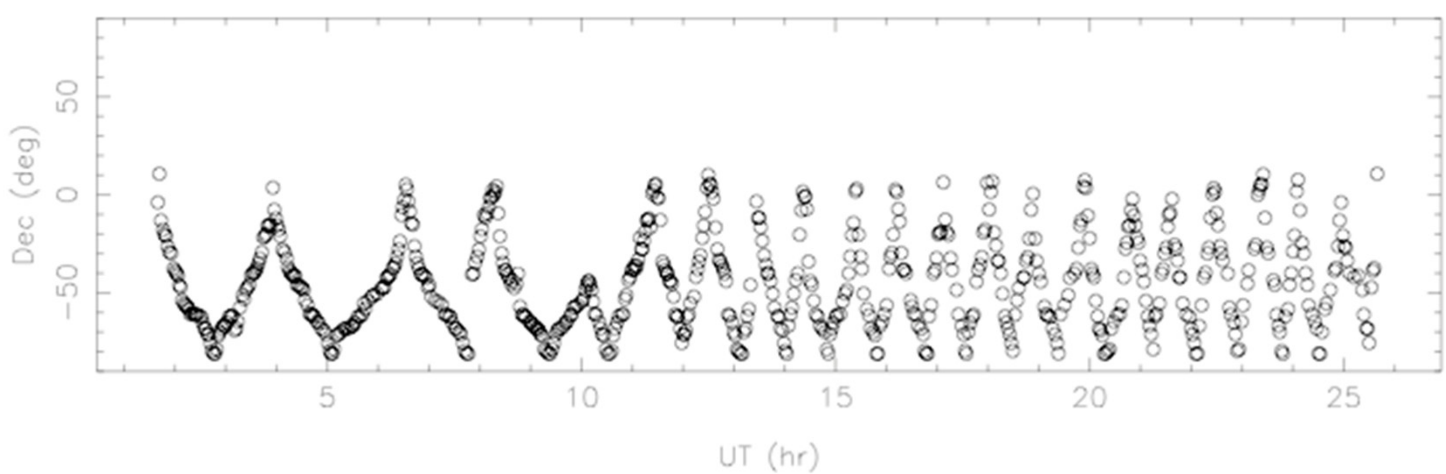

Credit: www.esa.int/esaMI/Operations/SEMGSDSMTWE_0.html

# DSS 34 to Malargue, Argentina (DSA-3)

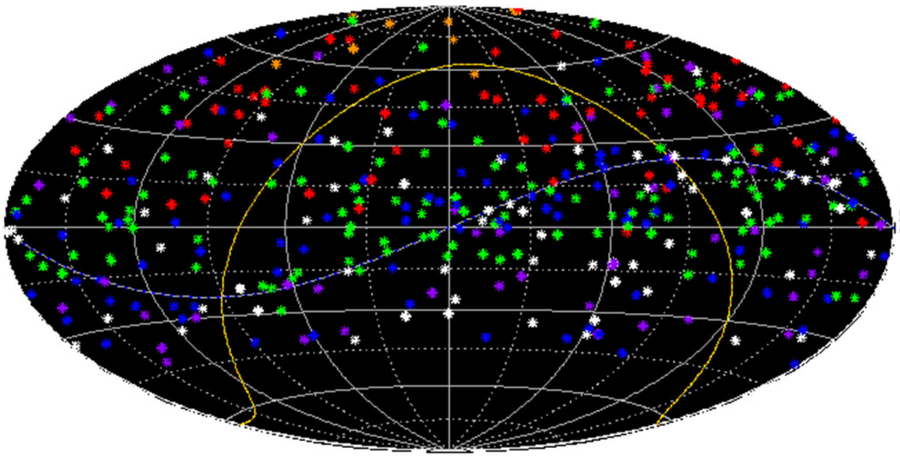


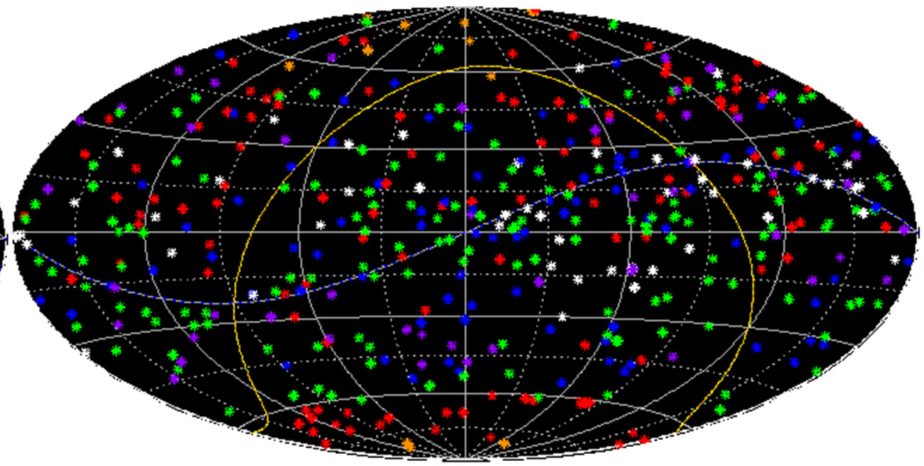




Simulated Coverage:
**Dec +10 deg to –90 deg**



# Simulation of Added Southern Station





*Before Southern Data* *After*

**Declination Sigma**

Orange: < 100 µas
Red: < 200
Green: < 300
Blue: < 500
Purple: < 1000
White: > 1000

- 50 real X/Ka sessions augmented by simulated data
  simulate 1000 group delays, SNR = 50
  ~9000 km baseline: Australia to S. America or S. Africa

- Completes Declination coverage: cap region -45 to -90 deg
  200 µas (1 nrad) precision in south polar cap,
  mid south 200-1000 µas, all with just a few days observing.

# Collaboration Plan

- Phase I: Build collaboration team:

  members in Spain, France, Germany, Australia, and U.S.

- Phase II: Test procedural and instrumental interfaces

  C. Garcia-Miro, M. Mercolino, C. Jacobs. Fringe tests: 2010/11

  Cebreros (DSA-2) to Robledo (DSS 65)

- Phase III: extend coverage to southern polar cap

  Lead: S. Horiuchi. Currently in planning stages.

  New Norcia (DSA-1) to Canberra (DSS 34)

  New Norcia Ka-band presently scheduled for 2015-16

- Phase IV: Improve accuracy to 70-100 μas

  Malargue (DSA-3) to Canberra (DSS 34): South polar cap & mid-south

  Malargue (DSA-3) to California (DSS 25), augments mid-south

  Target date: Fall 2012 when Malargue, Argentina comes online

# <u>Gaia-Optical *vs.* VLBI-radio</u>:

# Celestial Frame tie
# and
# Accuracy Verification

# Optical vs. Radio positions

Positions differences from:

- Astrophysics of emission centroids

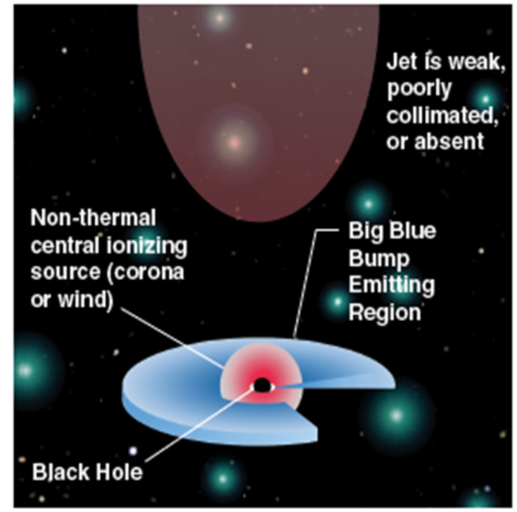
  - radio: synchrotron from jet

  - optical: synchrotron from jet?
    non-thermal ionization from corona?
    big blue bump from accretion disk?

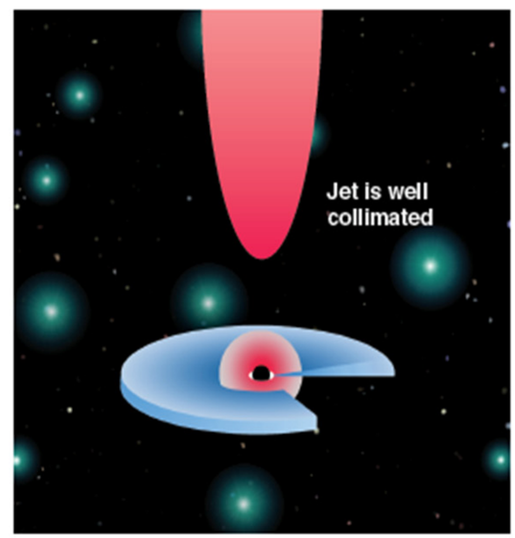
- Instrumental errors both radio & optical

- Analysis errors

Radio-quiet Quasar

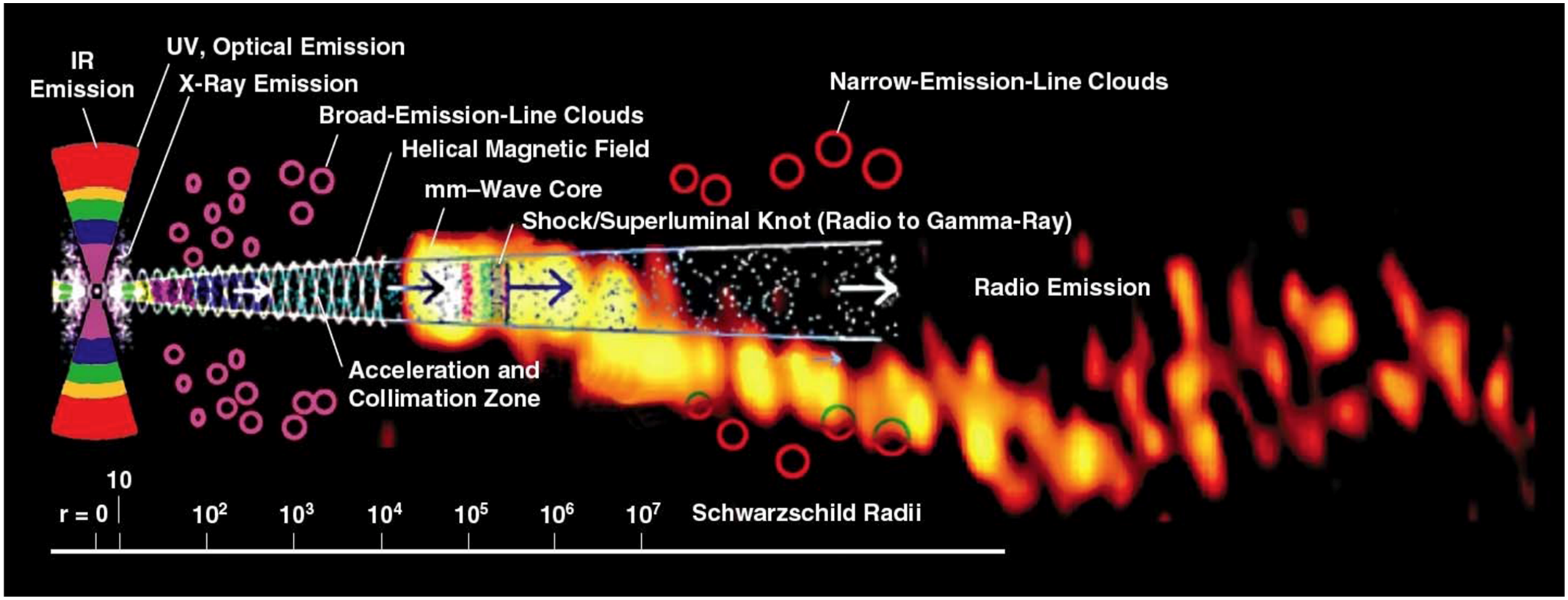



Radio-loud Quasar




Credit: Wehrle et al, μas Science, Socorro, 2009

# 9mm vs. 3.6cm? Core shift & structure




Credit: Marscher, 2006. Krichbuam, 1999.

Positions differences from 'core shift'

- wavelength dependent shift in radio centroid.
- *3.6cm to 9mm core shift:*

  100 μas in phase delay centroid?

  <<100 μas in group delay centroid? (*Porcas, AA, 505, 1, 2009*)
- shorter wavelength closer to Black hole and Optical: 9mm X/Ka better

# Gaia frame tie and accuracy verification

<u>Gaia: $10^9$ stars</u>

- 500,000 quasars V< 20
  20,000 quasars V< 18
- radio loud 30-300+ mJy
  *and*
  optically bright: V<18
  ~2000 quasars
- Accuracy
  70 μas @ V=18
  25 μas @ V=16

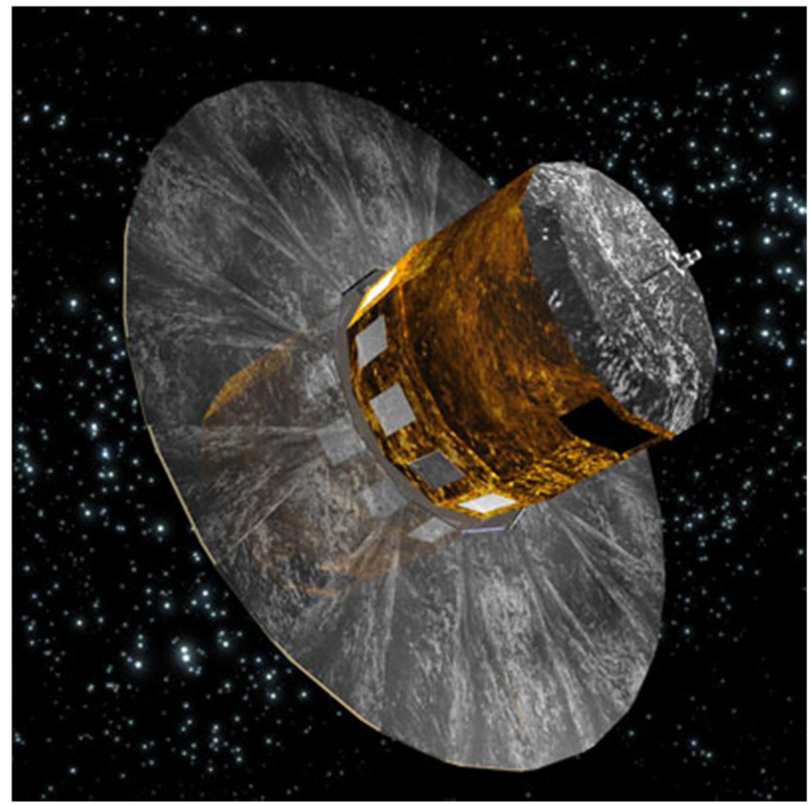
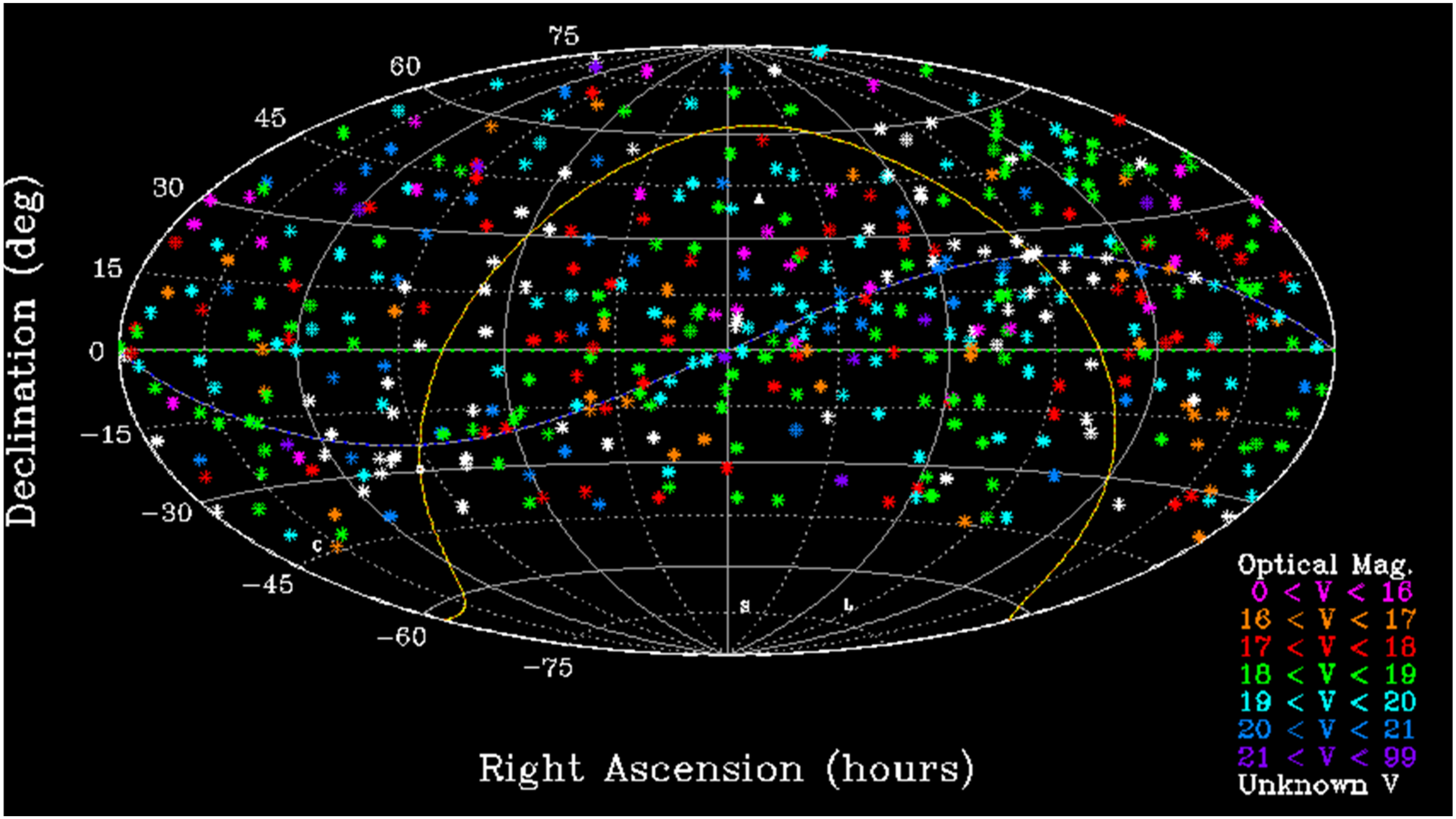


*Figure credit: http://www.esa.int/esaSC/120377_index_1_m.html#subhead7*

# Optical brightness of X/Ka 9mm sources




Median optical magnitude $V_{med}$ = 18.6 magnitude *(54 obj. no data)*

Thus ~200 objects optically bright by Gaia standard (V<18)

# Gaia Optical vs. X/Ka 9mm frame tie

- 306 X/Ka 9mm objects with known optical V magnitudes
  - ~200 objects optically bright ( V< 18)
  - ~100 objects optically weak (18 < V< 20)
  - ~ 100 objects optically undetectable ( V > 20)
  - ~ 50 objects *no optical info yet* ( *V = ?? )*
- Simulated Gaia measurement errors (sigma RA, Dec) for 306 objects: median sigmas ~ 100 μas per component
- VLBI 9mm radio sigmas ~200 μas per component and improving
- Covariance calculation of 3-D rotational tie using current, 9mm radio sigmas and simulated Gaia sigmas

  Rx +- 16 μas <- Weak. Needs south polar VLBI (Dec < -45)

  Ry +- 13 μas

  Rz +- 11 μas
- Now limited by radio sigmas for which 2-3X improvement possible. Potential for rotation sigmas ~5 μas per frame tie component

# Conclusions

- Astrometry using VLBI at 3.6cm, 1.2cm, 9mm
  ~1000 objects, 40-200 μas
    ~200 objects radio loud @9mm and optically bright V<18
- Quasar astrophysics: 9mm position closer to optical position
- Existing 9mm X/Ka catalog has 200 μas accuracy in North
  *improvements ongoing*
- ESA and DSN have *complementary* geometry
    ESA- DSN radio telescope collaboration has potential for
    Full sky radio coverage, 70-100 μas accuracy at X/Ka 9mm

- Benefits to ESA/Gaia of collaboration:
    Ties ESA-DSN terrestrial frames for navigation
    Ties Gaia optical to VLBI radio frame
    Independent check on Gaia accuracy at
        70-100 μas level for 200+ objects

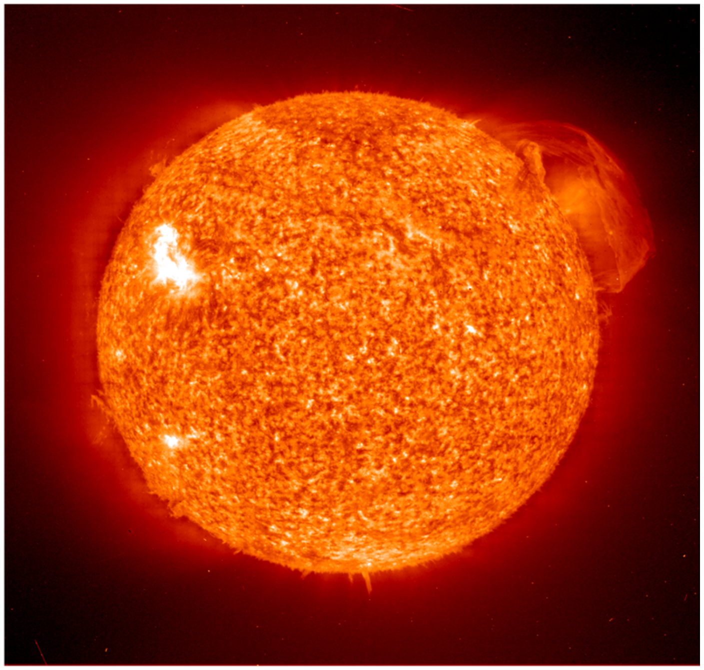
# BACKUP SLIDES

# Motivation for Ka-band: 9mm/32 GHz

- Astrometry, Geodesy and Deep Space navigation, have been at 3.6cm/8.4 GHz (X-band) with 2.3 GHz (S-band) plasma cals

Ka-band (9mm/32 GHz) provides

- More *compact* sources which should lead to more *stable* positions!
- Higher Telemetry Rates: +5 to +8 dB
- Smaller, lighter RF spacecraft systems
- Avoid S-band *RFI* issues
- Ionosphere & solar plasma down 15X !! at 32 GHz (Ka-band) compared to 8 GHz thus observe closer to Sun & Galactic center


Picture credit: SOHO/ESA/NASA

Drawbacks of Higher radio frequencies:

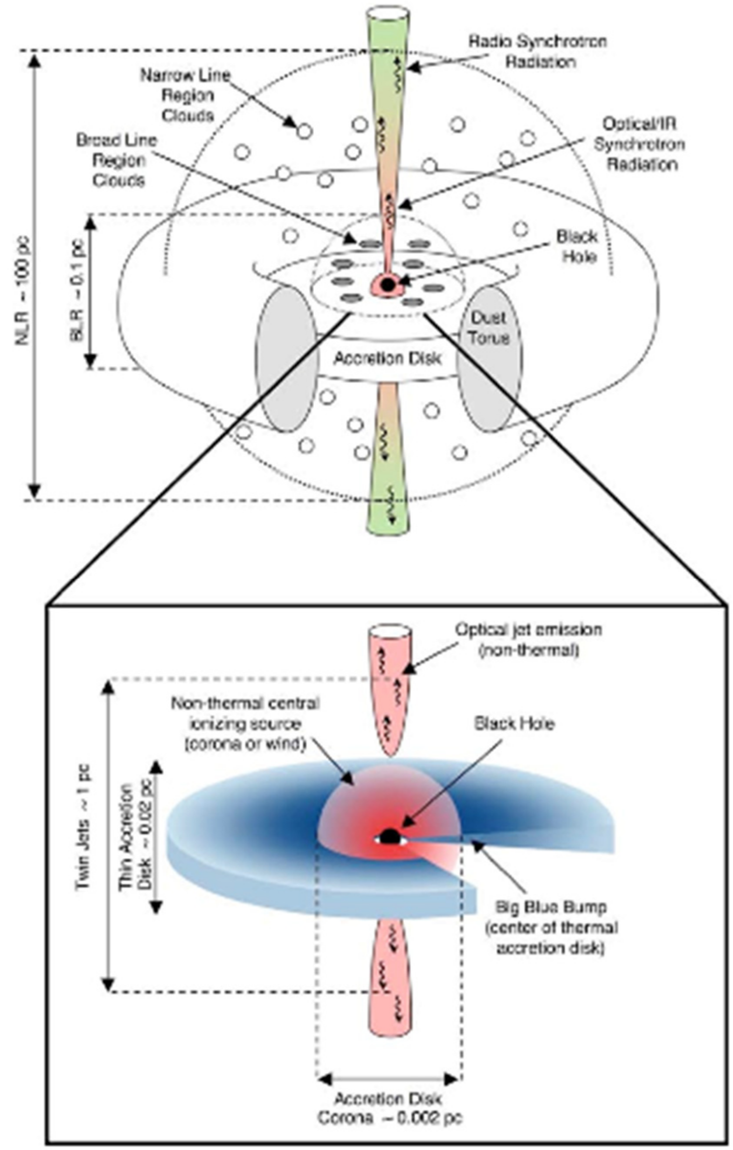
- More weather sensitive, higher system temp.
- Shorter coherence times
- Weaker sources, Many sources resolved
- Antenna Pointing more difficult

# Optical vs. Radio positions

Positions differences from:

• Astrophysics of emission centroids
  - radio: synchrotron from jet
    frequency dependent structure
    frequency dependent core shift

  -optical: synchrotron in jet?
   non-thermal ionization in corona?
   big blue bump?

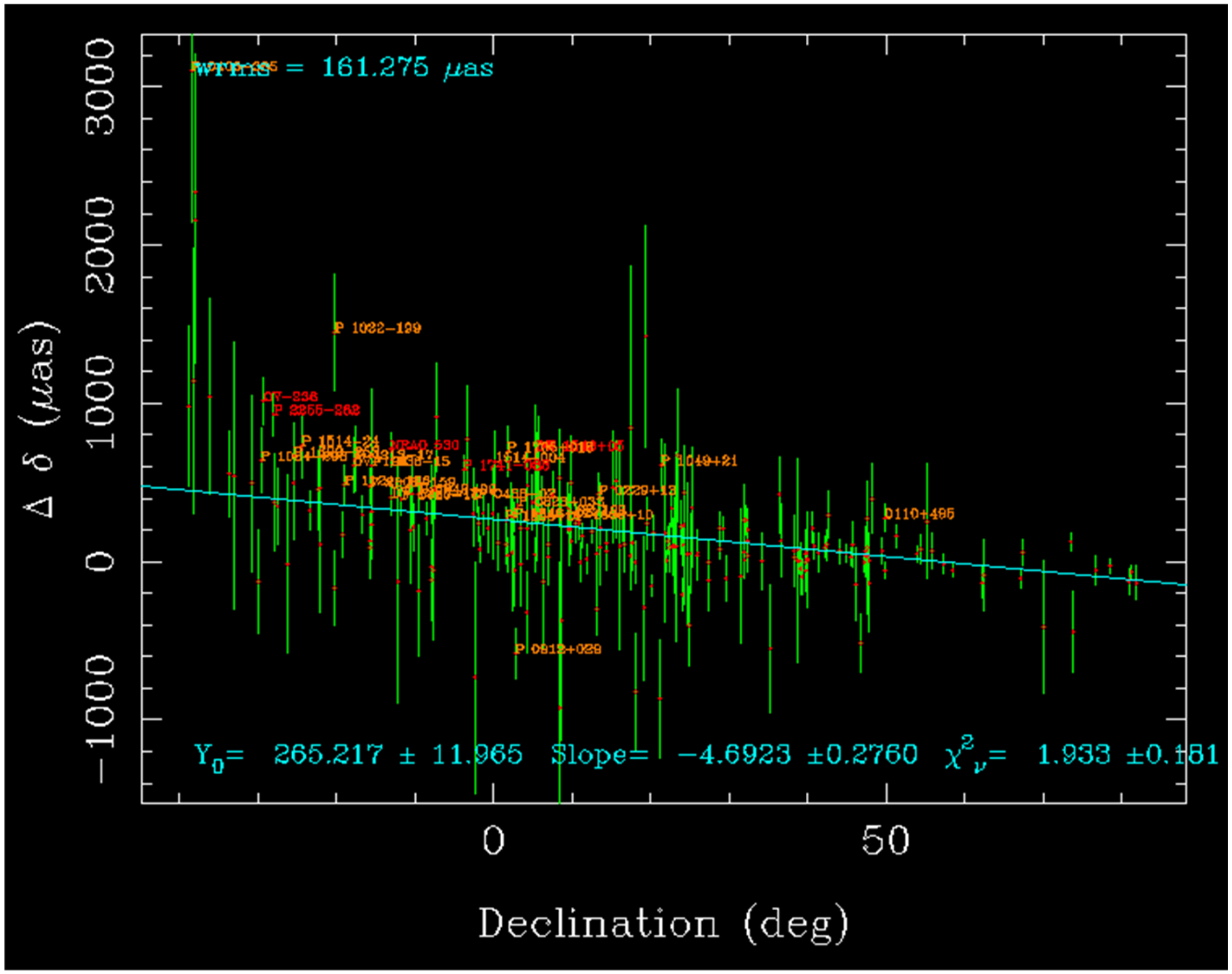



Credit: Elvis (2000) and Smith quoted in Unwin et al (2008)

# K-band 1.2cm *vs.* ICRF2 at 3.6cm (S/X)

Lack of direct
Dual-band ion
Calibrations
*and*
Lack of any
Station in south

Leads to poor
ΔDec vs. Dec
Zonal stability:
500 μas tilt




**K(1.2cm) Declinations vs. S/X ICRF2 (current IAU standard)**

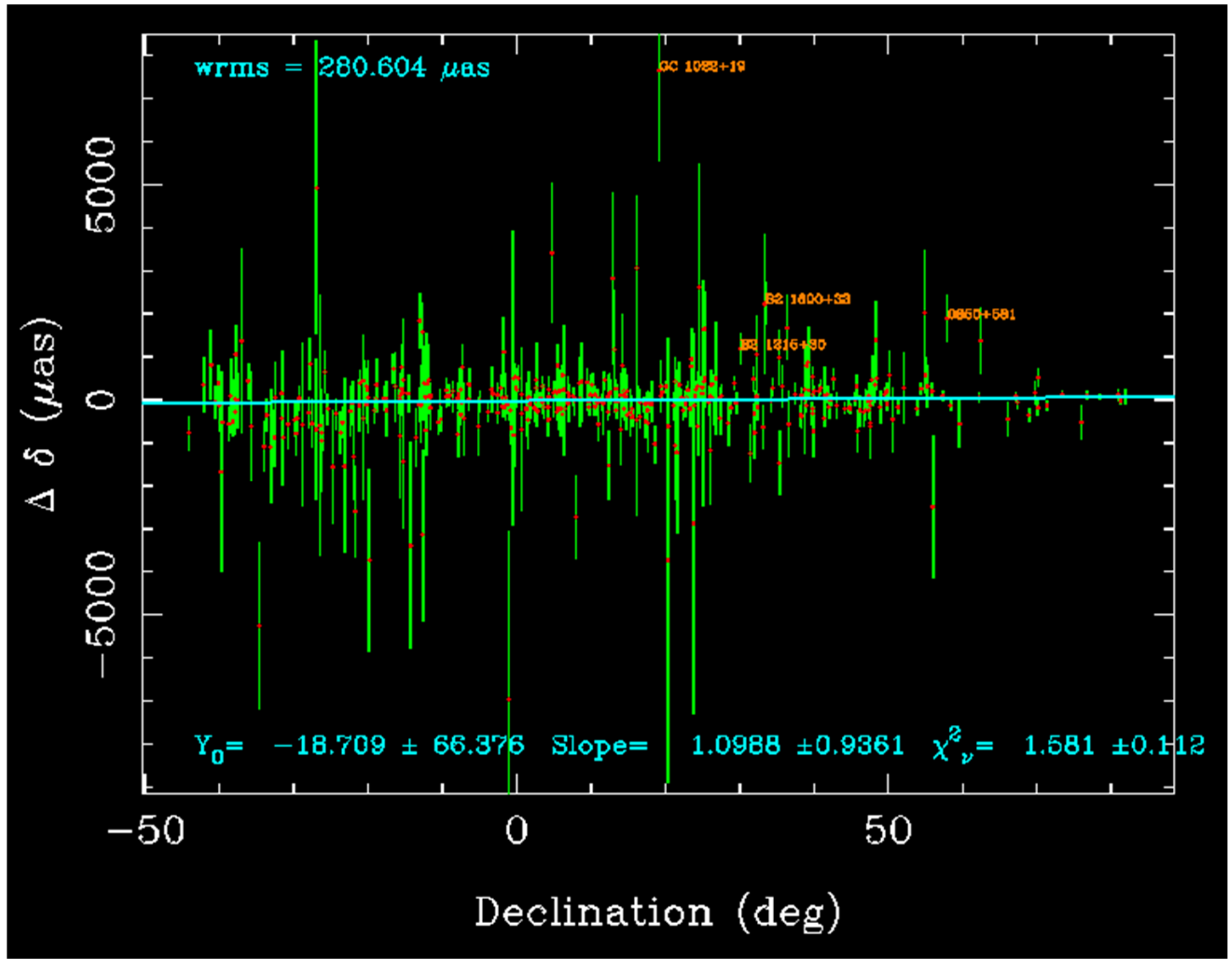
*Credit: K(1.2cm): Lanyi et al, AJ, 139,5, 2010*
*S/X ICRF2: Ma et al, editors: Fey, Gordon & Jacobs, 2009*

# 9mm (X/Ka) *vs.* ICRF2 at 3.6cm (S/X)

Dual-band ion
Calibrations
*and*
Station in south

Leads to better
ΔDec vs. Dec
Zonal stability:

100 ± 100 μas tilt




**X/Ka(9mm) vs. S/X ICRF2 (current IAU standard)**

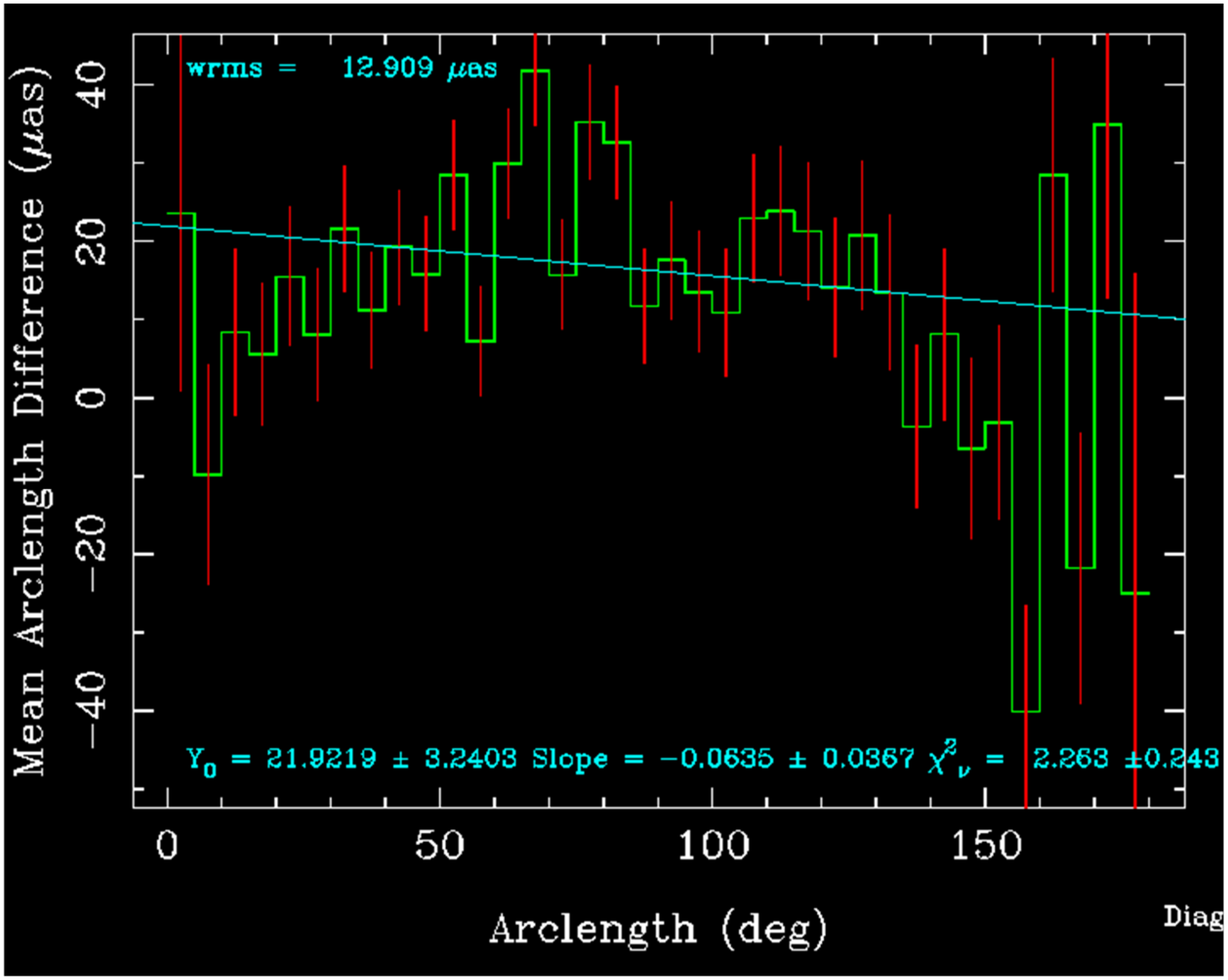
*Credit: X/Ka(9mm): Jacobs et al, EVGA, Bonn, Germany, 2011*
*S/X ICRF2: Ma et al, editors: Fey, Gordon & Jacobs, 2009*

# 9mm (X/Ka) *vs.* ICRF2 at 3.6cm (S/X)

Mean zonal error as shown by Δarc vs. arc ~20 μas (0.1 nrad)

When southern Station XYZ is fixed to S/X data estimate +-1cm.

Weaker constraint leads to 150 μas Zonal errors.




**X/Ka(9mm) vs. S/X ICRF2 (current IAU standard)**

*Credit: X/Ka(9mm): Jacobs et al, EVGA, Bonn, Germany, 2011*
*S/X ICRF2: Ma et al, editors: Fey, Gordon & Jacobs, 2009*